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ENERGY CONSUMPTION OF IP VS ETHERNET

School of Electrical Engineering

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ABSTRACT OF THE MASTERS THESIS

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Power or energy consumption is a very important parameter for planning and designing network elements for the future Internet. Research and development in energy consumption of network devices such as routers, switches, bridges, etc.is a major area where the industry and academia is currently focused. It is imperative that switches and routers provide a very high capacity and throughput for ever-growing user demands. Beside this high capacity they also need to be power efficient, highly reliable, and economical. So, it is necessary to develop devices that consume very low energy and at the same time serve with the highest possible capacity.

This thesis presents an analysis of a compiled set of database of power consumption and networking functionalities found in datasheets and manuals of routers and switches of some major manufacturers. This thesis gives general information of energy consumption of different vendors of routers and switches and also compares their energy efficiency. Graphs representing the general trend of energy consumption of the routers and switches over the years are shown. We found greater differences in power consumption between switches and routers of same capacity or data rate. Thus, the thesis analyzes the significance of such results and urges the network planners to design energy efficient routers or lead a discussion or approach in a way to completely replace the routers with the less energy consuming switches. Moreover, it also sheds some light on the most power consuming elements and networking features of routers that could be extremely useful in re-planning and operation of energy-efficient networks. Comparisons of the routers and switches of same vendors are done and the best among them is also analyzed.

Keywords: Ethernet, IP, Internet , MAC Addresses, Routers, Switches, TCP/IP, OSI Layer , Power and Energy consumption, Energy per megabit

Preface

This Master’s Thesis has been written as a partial fulfillment for the Master of Science (Technology) degree at the Department of Communications and Networking in Aalto University, School of Electrical Engineering, Finland.

At the end of my thesis, it is a pleasant task to express my thanks to all those who contributed in many ways to the success of this thesis. I am extremely indebted to my supervisor Professsor Jukka Manner for providing necessary guidance and support to accomplish my research work.

I take this opportunity to sincerely acknowledge Data Center of Finland (DC2F) for the partial financial support. I would also like to thank my friends especially Aashish, Prajwal, Gautam, Merina, Rajendra,Binod, Kendra,Mahabub and all other Aalto Nepalese for their helpful suggestions and constant encouragement.

Lastly and most importantly; I am grateful to my parents and sisters for continuously supporting me during every stages of my life.

Espoo, September 6, 2012

VivekAcharya

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Abbreviations

AP	Access Point
ARP	Address Resolution Protocol
BGP	Border Gateway Protocol
DHCP	Dynamic Host Configuration Protocol
DPC	DensePort Concentrator
EHWIC	Enhanced High-Speed WAN Interface Card
EU	European Union
FIB	Forwarding Information Base
FPC	Flexible PIC Concentrators
HP	Hewlett Packard
ICT	Information and Communication Technology
ISM	Internal Services Module
ISP	Internet Service Provider
LAN	Local Area Network
LLC	Logical Link Control
MAC	Media Access Control
Mbps	Megabits per second
MTU	Maximum Transfer Unit
MPC	Modular Port Concentrators
MPLS	Multi-Protocol Level Switching
OSI	Open System Interconnection
OSPF	Open Shortest Path First
PFE	Packet Forwarding Engine
POE	Power over Ethernet
QoS	Quality of Service

RIP	Routing Information Protocol
SFP	Small Form-Factor Pluggable
STM	Synchronous Transport Module
TCP/IP	Transmission Control Protocol / Internet Protocol
VPN	Virtual Private Network
VWIC	Voice /WAN interface Cards
WAN	Wide Area Networks

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1. Introduction

This chapter gives an introduction to the research work. First we discuss about the motivation and objectives along with the research questions. After that the research methodology is described. At last chapter the structure of the report is outlined.

1.1Motivation

Energy is an important aspect that drives the human life. With the evolution of the civilization, the human demand for energy has continuously risen and is also crucial for the continued human development [1]. Almost all the devices that are produced and developed today consume some sort of energy. Due to the growing human population, urbanization, and modernization the usage of these devices has increased rapidly. Consequently, energy is being consumed at an ever increasing rate. Unfortunately, this trend is also producing adverse effects in the environment by the pollution and undesired heating effects [2]. Thus, even if they are not already so, networking elements will be a major contributor of global warming and the climate change it entails [3, 2]. This is referred to as global warming [3]. Moreover, with depleting oil reserves of the world; the cost of energy is ever increasing in today's world. So reducing the energy consumption is becoming increasingly important with rising energy costs and environmental concerns [3, 1]. There are different forms of energy but we are talking about the electrical energy in general. Devices such as computers, TV, fans, generator etc. consumes electrical energy. It is now accepted that this electrical energy generation is a significant contributor to different greenhouse gases. So not only is energy consumption a key environmental issue these days, it also has wide reaching social and political dimensions [3, 4].

In the ICT field, the communication network is a major contributor to the total power consumption [5]. With the growth of Internet applications and devices and its adoption as the global information network, the amount of traffic flowing through the Internet has dramatically increased [6]. Therefore, the power required for routing and processing Internet traffic has been growing accordingly .Since the amount of IP traffic is increasing rapidly, the amount of equipment required to route this traffic must keep up with it [7]. This has led to the increment in number of the ICT devices such as routers, switches, bridges, hubs etc. As a consequence of this there is a growth in power consumption of this network equipment. This increase in power consumption is becoming a major barrier in continued bandwidth scaling of the Internet [8]. Also it has raised the issue of whether the Internet may ultimately be constrained not by the speed of routers, switches and other electronics devices but rather by their power consumption and energy efficiency.

As new high capacity elements are installed, energy consumption in network elements and exchanges is rising with higher capacity network equipment consuming larger portion of the energy [7]. We consider power management for networks from a perspective that has recently begun to receive attention i.e. the conservation of energy for operational and environmental reasons [3, 8]. So there has been a continuous concern regarding the power consumption of different network elements. The effort of bringing energy awareness in network elements and processes is usually referred to as green networking [9]. Also the global warming, energy costs, power consumption and heat dissipation in the communication systems and data center make energy efficiency an essential part of network research [2, 8]. The response of the research community to this increasing energy concerns has been not only to improve the hardware consumption but also to find methods to design and operate networks in a more energy efficient way. Design models have primarily been concerned with the trade-off of costs versus performance [6]. However, recently there has been an increasing number of energy-aware network design and operational methods aiming at reducing ICT energy consumption.

Routers and switches been an integral part of the ICT community, the study and analysis of routers, switches and their energy related issues has been an interesting topic for the research. A major difficulty for the assessment and continuations of the proposed and forthcoming set of network designs and planning of the routers and switches is the unavailability of the standard set of data that characterize their power consumption [6]. Therefore, there is an urgent need for the data and results from extensive and systematic testing of different manufacturers' product. This will eventually help to know the influences of their type, configuration and networking features in the overall power consumption so that further advancement can be made in the field of energy efficient network planning and operation [8]. Furthermore, comparison of energy consumption of the routers and switches and understanding the features, configuration and other functionality that made routers consume more power than switches is a good research area. As it is almost known that the routers which work on the third layer of OSI layer due to added functionalities on it consumes more power than switches which particularly works on the 2nd layer. Moreover, a possibility of whether the network routers could be eventually replaced by the switches or not might be a topic worth discussing.

1.2 Objective

This work has several objectives. First we want to set the basis for the evolving database of routers and switches that could be available for current and further studies in energy efficient network design and analysis. Secondly we want to know the general operation of the routers and switches. This includes the contents such as operation of routers, routing tables, different vendors of routers, operation of switch, MAC table and different vendors of switches available in the market etc. The main objective of this work is to determine and find out the energy per bit consumption of IP and Ethernet i.e. the routers and switches. This enables us to find the general energy consumption trend of the routers and switches in different years. Apart from this, we also want to quantify through the databases analysis, the real extent of some known differences in consumption such as the routers having more power consumption than the switches. This is studied and analysed by different additional features, functionalities and interfaces that the routers possess. The comparison of the routers and switches of same vendor released in the same year are also considered and their power requirements are also analysed. Finally we also want to create awareness on the power consumption impact of networking functionalities and open the discussions on the necessity or possibility of more energy consuming devices such as routers replacing by the low energy consuming switches.

Having discussed the objectives of the research work we now state the research questions which guide for the course of our research work. Following are the research questions we primarily focus on:

- *What are the different vendors of routers and switches that are available in the market?*
- *How do the routers and switches work?*

- *When are the different products of routers and switches released and been available in the market for the commercial use?*
- *How is the general energy consumption trend of these devices in different years?*
- *Comparison of energy consumption of IP and the Ethernet i.e. the routers and switches?*
- *Why do the routers consume more power than the routers?*
- *Discussions on whether the routers can ultimately be replaced by the switches only?*

1.3 Research Methodology

In this thesis the collection of the data is the most important part. It is converted to uniform unit and then analysed. Collection of the data is one of the challenging jobs. It requires lots of internet accessing. Data related to different vendors of routers and switches such as Juniper, Cisco, D-link, HP and Brocade were collected. For both types of devices the information collected are the maximum power consumption in watts, the maximum capacity in Gigabit per second (Gbps), release dates in year, the type of available and supported interfaces or ports.

Data related to different vendors of routers and switches are collected from the Internet. In order to understand the energy trends depending on both the aggregated capacity, power consumption of different generations of routers and switches are assessed. In the case when there are many products of same vendors in the same year the average energy per bit of those devices are taken. Also the maximum and the minimum energy per bit requirement of those devices are also shown. Websites of different companies related to the manufacture of routers and switches are browsed. Catalogue, brochure's related to different series or vendors are looked upon. The calculations of power requirements are performed on the basis of the data collected from the technical data sheets of the commercial equipment. The searched data are kept in a small database. The searched data are basically release dates, power consumption, power dissipation, capacity, average energy dissipation of the routers and switches. The vendors were also directly contacted to provide the relevant data. In some cases, they gave the relevant information which has been used in the thesis. The careful analysis on collected data is done from the database.The overall research process is summarized in ***Figure 1.***After this, the data in the database are used to calculate the energy per bit of the products. So the energy per bit (joules/ bit) is calculated from the data rate which is in Gbps and the power consumption that is in watts. The calculation is as follows:

Power = Energy / time

Data-rate = bits/time

Energy per bit = Energy/bits

= Energy/time)/ (bits/time)

= Power/data-rate

*= Power/ (1,000*data-rate) in J/megabit*

When power is given in watts and data-rate is given in Gbps

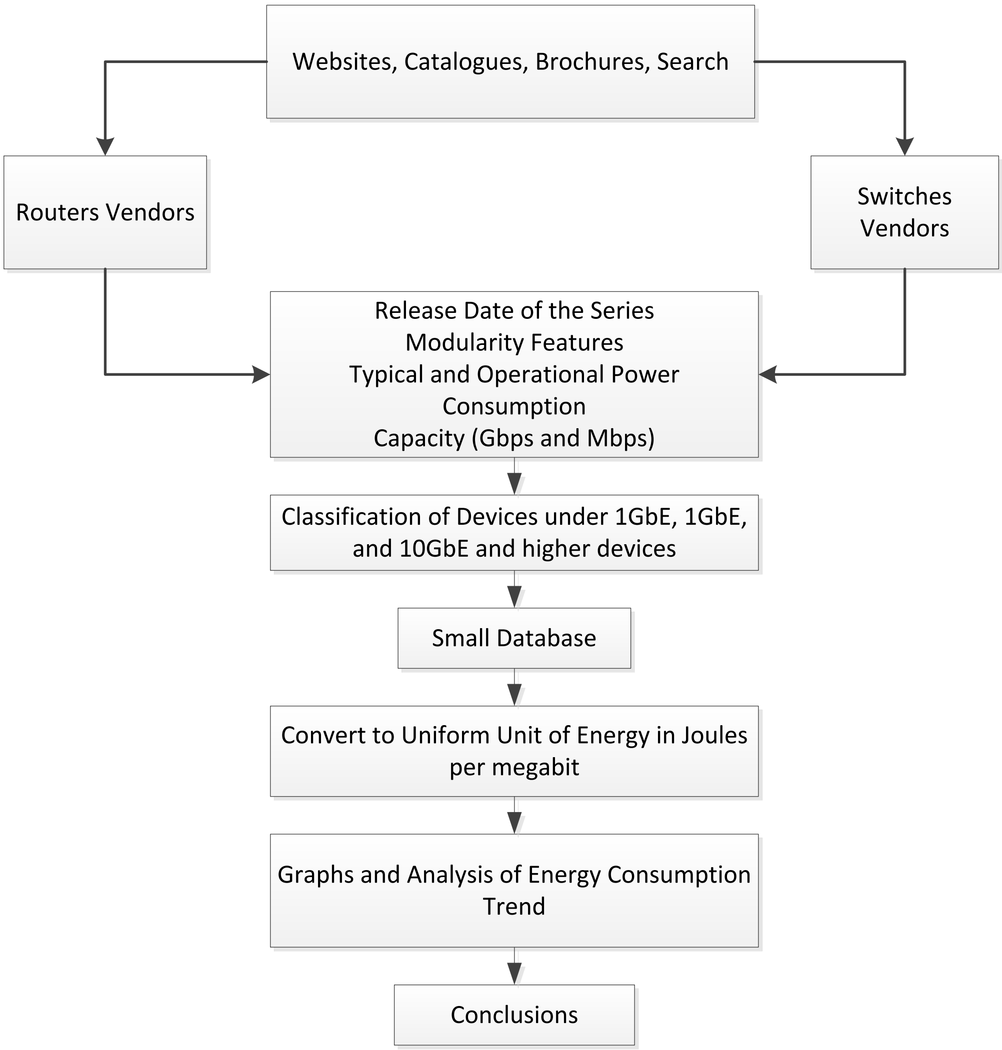

Figure 1: Research Methodology

In ***Figure 1***the research methodology of the thesis is presented. It gives in detail the processes that are done to achieve the objective of the work.

1.4 Structure of the Report

The thesis is structured as followed. In Chapter 2 we discuss purely about IP routing and different vendors of routers. Chapter 3 talks about Ethernet and switches including their products. The existing analysis about energy consumption and the research work on energy efficiency of routers and switches are discussed in the fourth chapter. Finally, in Chapter 5 we draw conclusions by reviewing how effectively we were able to meet the objectives of the research work.

2. IP Routing

This chapter gives the information about TCP/IP, addressing in IP, routers, operation of routers, routing algorithm and different vendors of routers. Also, it presents different features of different series of routers related to different manufacturers.

2.1 TCP/IP

Internet has revolutionized the computer and the communications world. The history of computers began with the point to point communications between the mainframe computers and terminals and expanded to connection between computers and networks [10]. Development of packet switched networks such as ARPANET led to the development of protocols for internetworking in which multiple separate networks could be joined together [11]. In the 1960s, American military created a protocol that would enable the standardized exchange of information between various networks regardless of its hardware and software [11]. This was together called as the TCP/IP. TCP and the IP are always taken together but these are two different things. TCP operates at the higher level than the IP and provides communication services at the intermediate level between an application program and the IP. So TCP is mainly responsible for the transporting of the data. Transporting refers to reliable data transfer from one device to another and is also in charge of controlling size, flow control, rate of data exchange and network traffic congestion. On the other hand IP is responsible for the actual addressing and delivery of the data packets from the source host to the destination host. Basically, the IP is the internet protocol that comprises of running over the Ethernet and operating in the link. There is a seven layer OSI model that is used to describe networks and network application. The TCP/IP model uses four layers that logically span the equivalent of the top six layers of this OSI model. So it is possible to assemble an indefinite number of individual networks into an overall network through the IP [12].

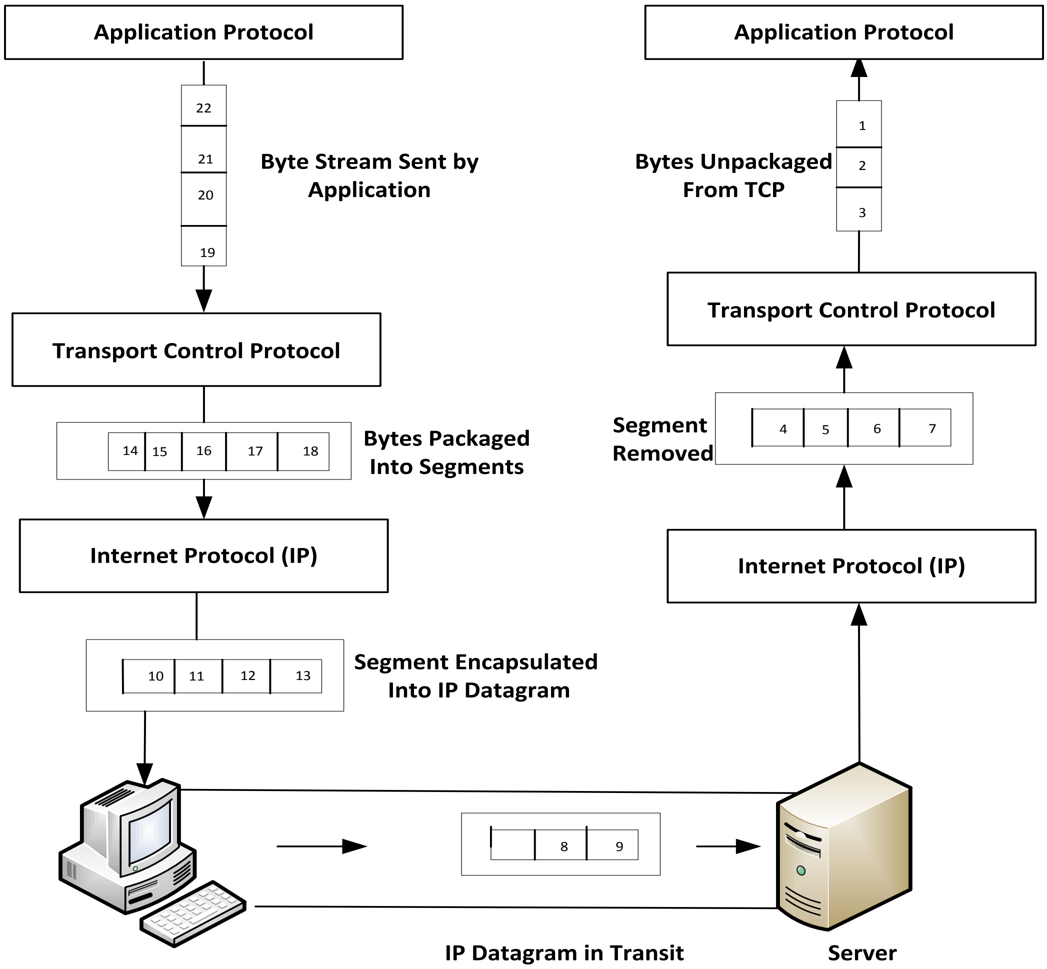

Figure 2: TCP Data Stream Processing and Segment Packaging [13]

Figure 2 presents the data streaming and segment packaging process. Here, the TCP segments are treated like all other messages used for transmission by the IP. They are placed into the IP datagram and transmitted to the destination device. The recipient unpacks the segments and passes them to the TCP, which converts them back into a byte stream to send to the application.

2.2 OSI layer

There are seven layers in the OSI model. Physical layer deals with the electrical and radio signals and conveys into bit stream. In the Data link layer data packets are encoded and decoded into bits and it also handles error in the physical layer, flow control and frame synchronization [12, 13]. Network layer provides routing and switching technologies whereas the transport layer is responsible for the transparent data transfer between end systems. The session layer establishes, manages and terminates connections between the applications. The function of the session layer is to transform the data into the form that the application layer can accept. Application layer supports applications and end user processes. This layer provides services for file transfers, e-mail, and other network software services e.g. Telnet, FTP. These seven layers logically equivalent to the 4 layers of the TCP/ IP model which is shown in ***Figure 3.***

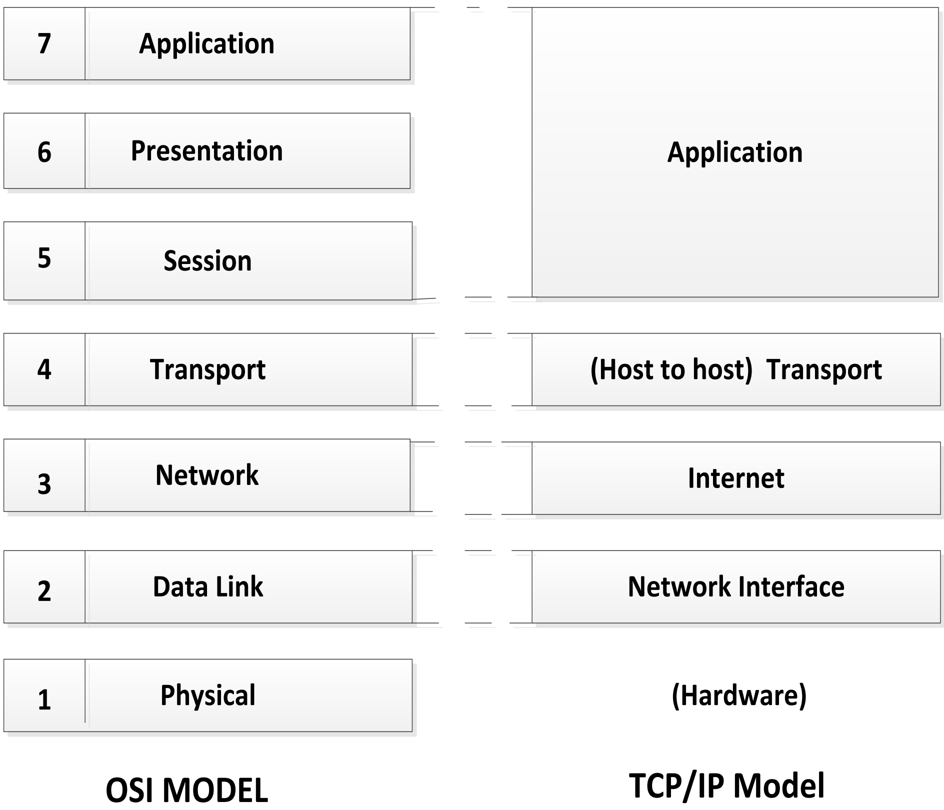

Figure 3: OSI and TCP/IP Model

Internet protocol (IP) is the principal communication protocol which is responsible for routing data packets across the network boundaries [10]. It functions on the 3 layer of the OSI reference layer also known as the network layer. So, it has the task of delivering the datagrams from the source host to the destination. For this purpose IP defines IP datagram structure which encapsulates the data to be send.

2.3 IP Datagram Format

The format of the IP Datagram along with the number of bits required is shown in the ***Table 1***. The format consists of version, header length, service type and the total length.

Table 1: IP datagram format

<table>
<tr><th>Version(4 bits)</th><th>Header length(4 bits)</th><th>Service type (8bits)</th><th colspan="2">Total length (16 bits)</th></tr>
<tr><td colspan="3">Identification (16 bits)</td><td>Flags(3 bits)</td><td>Fragment offset(13 bits)</td></tr>
<tr><td colspan="2">Time to live(8 bits)</td><td>Type (8bits)</td><td colspan="2">Header checksum (16bits)</td></tr>
<tr><td colspan="5">Source IP address (32bits)</td></tr>
<tr><td colspan="5">Destination IP address (32bits)</td></tr>
<tr><td colspan="4">IP Options (may be omitted)</td><td>Padding</td></tr>
<tr><td colspan="5">Data</td></tr>
</table>

2.4 Addressing in IP

IPv4 addresses are 32 bits in length. IP addresses are hierarchical for routing purposes and are subdivided into two subfields which are Network Identifier and the Host Identifier [14]. For the purpose of accommodating different size networks, IP defines several address classes. The features of each address class are shown in the ***Table 2.***

Table 2: Addressing in IP

Network bits	**Host bits**	**Decimal address range**	**Class**	**Subnet Mask**
8 bits	24bits	1-126	A	255.0.0.0
16 bits	16 bits	128-191	B	255.255.0.0
24 bits	8 bits	192-223	C	255.255.255.0
Reserved for multicasting		224-239	N/A	D
Reserved for R&D		240-255	N/A	E

2.5 Routers

Routers are intermediate devices which operate at the network layer of the OSI reference model. Routers are basically pieces of equipment, with a primary objective of serving as a hardware platform for routing data packets between networks [16]. It consists of a computer with at least two network interface cards supporting the IP protocol. The router receives packets from each interface via a network interface and forwards the received packets to an appropriate output network interface [17]. A router is located at any point of network. The router is connected to at least two networks and it makes a decision which way to send each data packet based on its current state of the network it is connected to. So it determines the next network point to which a packet should be forwarded toward its final destination. A router creates and also maintains a table of the available routes and their conditions. Then this information along with distance and cost algorithms are considered to determine the best route for a given packet [18]. Typically, a packet may travel through a number of network points before arriving at its final destination. Received packets have all link protocol headers removed, and transmitted packets have a new link protocol header added prior to transmission [19].

a) Linksys router

b) D-link router

Figure 4: Examples of Routers [21]

Basically, routing is a way to get packets from one destination to the other .So it is the way of finding a path from a sender to a desired destination. In IP this reduces the task of finding series of routes between the source and destination networks. As long as a datagram or message remains on single network, any forwarding problems that arise are the responsibility of technology that is specific to that particular network [19]. Routers can be divided into two main components which are a routing engine and a forwarding engine [20]. Routing engine is responsible for processing the routing information such as to compute the shortest path using the suitable algorithms, knowing the destination addresses, next-hop interface, and a metric. Routing entries are made to populate the forwarding information base (FIB) whose entries are used by the forwarding engine [20]. The main function of the forwarding engine is to transfer incoming traffic to a destination looking upon the information of the FIB. The basic structure of the IP router architecture is shown in the ***Figure 4***.

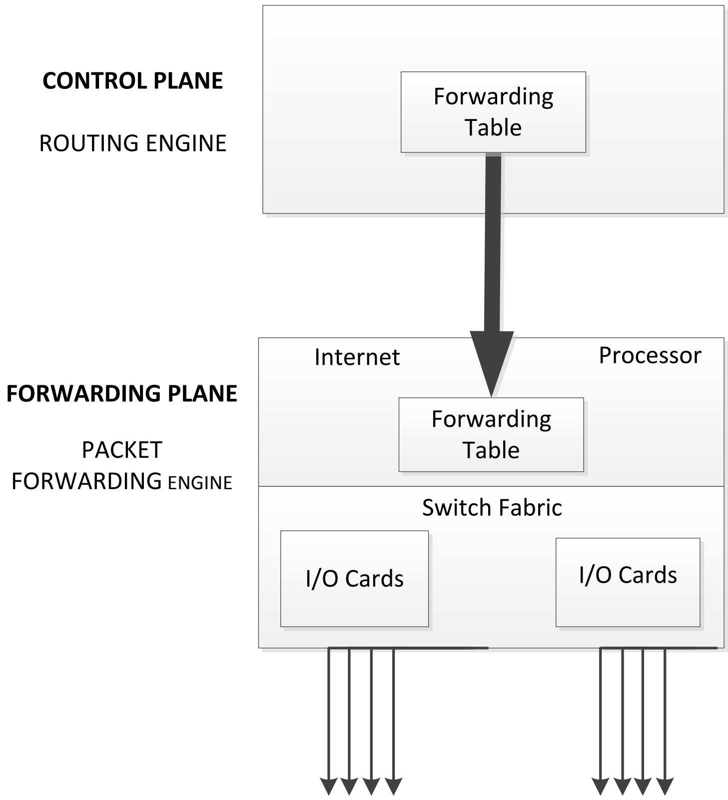

Figure 5 : Modern IP router Architecture [19]

Many networks and intermediate systems can be interconnected to form a more complex set of interconnections using the routers. As the network topology becomes complex then the simple network-to-network packet forwarding will no longer suffice and a routing protocol must be employed so that a server can become aware of all happening around the networks [19]. ***Figure 6*** shows the interconnection of three networks with the help of the two routers.

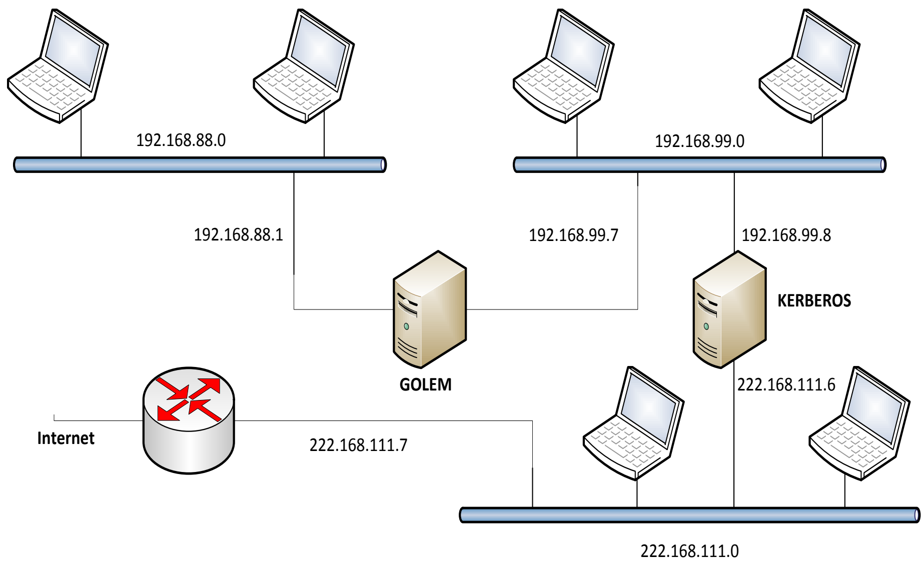

Figure 6: Three LANs interconnected by two NT server-based routers [26]

2.5.1 Operation of Routers

The routers use the information held in the network layer header (i.e. IP header) to decide whether to forward each received packet, and which network interface to use while sending the packet [18]. Most packets are forwarded based on the packet's IP destination address along with routing information available in a routing table within a router. Before a packet is forwarded, the processor checks the Maximum Transfer Unit (MTU) of the specified interface [21]. Packets which are larger than the interface's MTU are fragmented by the router into smaller packets. But, when a packet is received with a Don't Fragment (DF) bit set in the packet header, the packet is not fragmented, instead it is discarded. In this case, an error message is returned to the sender informing it of the interface's MTU size [18, 21].

Routing table is an important part of routing process. It is a data table that is stored in a router or in a networked computer that contains the routes to particular network destinations. The table is a small in-memory database managed by the router's built-in hardware and software [15]. In some cases, metrics that are associated with those routes are also listed in it. The table also contains information about the topology of the network around it. Most nodes in the network don’t figure out which route might work. Instead, it will send an IP packet to a gateway in the LAN, which decides the way of delivering the packets to the required destination [22]. Each of the gateways uses the routing table to know how to deliver various packages of data. So routing table allows keeping track of paths and allows the gateway to provide information to the node requesting the information. The structure of routing table contains all the information that is necessary to forward an IP data packet toward its destination. Each routing table entry labels the collection of best paths to a particular destination. Open Shortest Path First (OSPF) is used for a default route. There is a single routing table in each router. In case of forwarding an IP data packet, the routing table entry providing the best match for the packet destination is located and the matching routing table entry provides the next hop towards the packet's destination [23].

The basic routing table consists of the network id; cost i.e. the cost or metric of the path through which the packet is to be sent and the next hop or gateway, which is the address of the next station to which the packet is to be sent on the way to its final destination.

Table 3: Basic contents of routing table

network id	cost	next hop
……	…….	……

The fields found in the routing table entry are as follows:

Destination type is either network or router. Only network entries are used when forwarding IP data traffic. A network is a range of IP addresses, to which IP data traffic may be forwarded. This includes different IP networks such as class A, B, or C, IP subnets, and single IP hosts. The default route also falls into this category. Destination ID refers to the destination's identifier or name. This depends on the destination type as well. For networks, the identifier is their associated IP address. For routers, the identifier is the OSPF Router ID.

Address Mask: It is only defined for networks. The network's IP address together with its address mask defines a range of IP addresses. For IP subnets, the address mask is referred to as the subnet mask.

Interface: The outgoing network interface the device should use when forwarding the packet to the next hop or final destination.

It's been obvious now that the main purpose of routing is to find a way to get datagrams or packets to their ultimate destinations. Routes are based on a table in each router listing the best route to every destination in the system. So, in order to define which route is best, we need to have some way of measuring it which is referred to as metric. Most of the common metrics used are as follows.

- Path Length
- Reliability
- Delay
- Bandwidth
- Load
- Communication Cost

2.5.2 Routing Algorithms

Different routing algorithms use different metrics to determine the best route. Routing algorithm is a formula that is stored in the router's memory whose main purpose is to make decisions for the router concerning the best paths for data [24, 25]. The router uses routing algorithm for computing the path that would best serve to transport the data from the source to the destination. There are two major types of routing algorithms that can be used by routing protocol which are distance vector or link-state.

A distance vector algorithm uses metrics known as costs to determine the best path to a destination. The path with the lowest total cost is chosen as the best path. In this case different costs are gathered by each router. These costs can be completely arbitrary, administrator-assigned numbers, dynamically gathered values, such as the amount of delay experienced by routers when sending packets over one link as opposed to another etc. [22]. All the costs are compiled and placed within the router's routing table and then are used by the algorithm to calculate a best path for any given network conditions. The core concept of what distance vector algorithms are and how they compute their decisions is by adding the metrics for every optional path on a network so that at least one best path is found out[24]. The formula for this is as follows:

$$M(i,k) = \min\,[M(i,t) + M(t,k)] \ldots\ldots [25]$$

This formula gives the best path between two networks (M (i, k)). It can be found by finding the lowest (min) value of paths between all network points. RIP is a popular routing protocol that uses this algorithm.

Link state algorithm also work in the same basic framework as that distance vector algorithms do, in that they both favor the path with the lowest cost. It computes the path that is related to the most immediate or direct links. This type of algorithm is most suitable to the less changing environment conditions. Here, the router simply needs to know which one of its direct interfaces will get the information where it needs to go the quickest. The most beneficial thing is that the routing protocol doesn’t need to make bigger routing tables as the routing table contains much less information due to the direct interfaces [24]. OSPF is the example of this link state algorithm.

2.5.3 Routing Protocols

We have routing protocols using different routing algorithms. Most used routing protocols are RIP and OSPF. Both of these use different types routing algorithm to help the router move data. RIP follows the distance vector algorithm while the OSPF uses the link state algorithm. RIP advertises the network updates periodically and advertisement is sent every 30 seconds [26]. It also triggers the updates whenever a change happens in the network. It supports the maximum of 15 routers and 16th hop [26]. Mainly three versions of RIP namely RIP V1, RIP V2 and RIPng are available. RIP V1 and RIP V2 are supported in the IPv4 environment whereas the RIP next generation is implemented with IPv6 [22]. Other important protocol is the OSPF. Here a shortest path is chosen. Since it doesn’t have the maximum hoop count of the routers it is widely used in large networks. RIP uses a lot of bandwidth as it sends periodic updates whereas OSPF advertises only changes in the network [25]. OSPF is the most used protocol in recent times. The information being passed to the routing algorithm within the routing table is gathered by the routing protocol known as a routing update process.

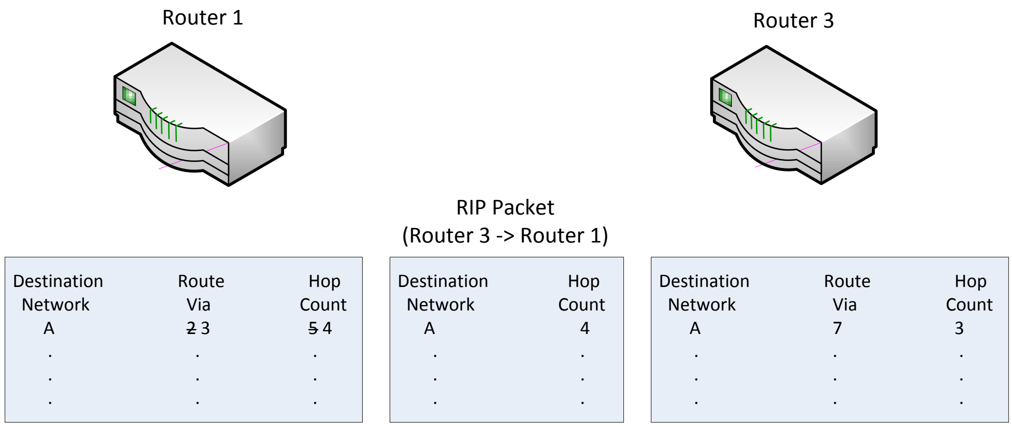

Figure 7: RIP packet from Router 3 to 1, and update of Router 1's routing table[26]

Figure7 is a simple example of RIP routing table which shows the routing tables update process between the two neighboring routers. Router 1 has the information of the network A and shows that it is 5 hop counts away if it takes the route via router 2. Also router 3 tells that it is only 3 hop counts away if it routes through router 7. The entry for Network A in the advertisement shows a hop count of 4 because all neighbors of Router 3 are 4 hops from Network A. Now if the neighbor routes via router 3 its router 3´s responsibility to increment the table before broadcasting its routes. In such a case the router 1 also feels that it is better to route through route 3 to Network A and updates the table accordingly.

2.6 Types and Vendors of Routers

Several types of routers such as broadband, wireless, edge, core subscriber edge routers etc. are found in the market. Broadband routers can be used to connect to the Internet or to connect computers. Wireless routers are used to create a wireless signal in your home or office whereas the edge routers are placed at the edge of ISP network and are normally configured to external protocol like Border gateway protocol (BGP) to another BGP of other ISP [27]. Subscriber Edge Router belongs to an end user organization and is configured to broadcast external BGP and the core routers resides in the middle of LAN network and interconnects the distribution routers from multiple building of a LAN, or Large enterprise Location (WAN) [22, 26] . Depending upon the capacity and power requirements there are many vendors of routers available in the market such as the Cisco, Juniper, Brocade, D-link, HP, Avaya, Linksys etc. The market consumption of the routers depends upon the performance and most importantly the price of the device.

2.6.1 Cisco Routers

In this analysis commonly available Cisco routers are used. Mostly different Cisco series routers such as 2900, 2800, 3900, 1941, 1800, 7200, 7500, 7600 and RVS4000 are taken into consideration.

2.6.1.1 Cisco 2900 Series

These series include Cisco 2901, 2911, 2921, and 2951 routers. These are introduced in the market in the year 2006. These routers offers embedded hardware encryption acceleration, optional firewall, voice- and video-capable digital signal processor slots, intrusion prevention, call processing, voicemail, and application services in all of them. In addition, the platforms also support wired and wireless connectivity options such as T1/E1, T3/E3 and Gigabit Ethernet fiber [28].

The cisco 2900 series router has different modularity features such as the different Cisco Service Module and Cisco Enhanced High-Speed WAN Interface Card (EHWIC) [28]. These affect the total power consumption of the routers and their overall performance. Each of the service module slots offers high-data-throughput capability and offers up to 4Gbps aggregate toward the route processor and up to 2Gbps aggregate to other module slots over MGF (Multi gigabit fabric). The EHWIC slot provides enhancements to high-speed WAN interface card (HWIC) slots which also provide maximum investment protection by supporting WAN interface cards (WICs), voice interface cards (VICs), and voice/WAN interface cards (VWICs). Four integrated EHWIC slots are found on the Cisco 2901, 2911, 2921, and 2951 which allow for more flexible configurations. Each HWIC slot offers high-data-throughput capacities near to 1.6Gbps aggregate toward the route processor and up to 2Gbps aggregate to other module slots over the MGF. Each Cisco Internal Services Module (ISM) slot also offers high-data-throughput capability and the capacity of near to 4Gbps aggregate toward the route processor and 2Gbps aggregate to other module slots over the MGF.

2.6.1.2 Cisco 2800 Series

In this series we have different Cisco products namely 2801, 2811, 2821, and 2851 which were released in the market in the period of 2004. The Cisco 2800 series modular architecture has been designed to support increasing bandwidth requirements, timedivision multiplexing interconnections, and fully integrated power distribution to support different modules. Different NME slots and Cisco Enhanced High-Speed WAN Interface Card (EHWIC) are present which affects the total power and the capacity of the routers. The NME slots support on Cisco 2811, 2821, and 2851 only. NME slots offer high data throughput capability up to 1.6Gbps and support for Power over Ethernet (POE). NME slots are highly flexible with future support for extended NMEs as well. There are four integrated HWIC slots on Cisco 2811, 2821, and 2851 and two integrated HWIC slots on Cisco 2801 which allow for more flexible and dense configurations. Besides these HWICs slots can also support WICs, VICs, and VWICs. This HWIC slot offer high data throughput capability near to 800 Mbps and also supports POE [29].

2.6.1.3 Cisco 3900 Series

The Cisco 3900 series contains 3945E, 3925E, 3945, 3925 routers which were released in the period of 2008 in the market. These series routers offer increased levels of services integration with voice, video, security, mobility, and data services and also provides the highest performance and slot densities among the routers in the Cisco ISR G2 portfolio. The modules used on this series can easily be supported on other routers in this Cisco ISR G2 portfolio enabling us to maximize services integration. Here highly flexible service-module slots replace the network module and the extension module. Each service-module slot offers high data-throughput capability which is up to 4-Gbps aggregate capacity toward the router processor and 2-Gbps aggregate capacity to other module slots over the MGF. Three integrated EHWIC slots are found on Cisco 3945E, Cisco 3925E and four integrated EHWIC slots on Cisco 3945 and Cisco 3925 offers flexible configurations. Each of the HWIC slot increases the performance of the router to 4-Gbps and aggregate capacity of 2-Gbps to other module slots over the MGF [30].

2.6.1.4 Cisco1941

This is one of the product of the 1900 series Cisco routers and was released in the year 2003.The Cisco 1941 router delivers highly secure data, mobility and application services. It has 2 Enhanced High-Speed WAN Interface Card slots and has fully integrated power distribution to modules supporting power over Ethernet (P0E) [31]. Also 2 integrated 10/100/1000 Ethernet ports are also available. Each HWIC slots aggregate capacity towards the router processor =2*1.6Gbps =3.2Gbps

2.6.1.5 Cisco 1841

This is the product of the 1800 series Cisco routers and was released in the year 2002.The Cisco 1841 router is specifically designed to meet requirements of small to medium-sized businesses and small enterprise branch offices. The modular architecture of Cisco 1841 router supports 2 HWIC slots [32,33]. These slots increase the data-throughput capability of 800Mbps and provide compatibility with WICs. Each HWIC slots aggregate capacity towards the router processor =2*800Mbps =1.6Gbps.The features and components of the Cisco series 3900, 2900, 1941 and 1841 are tabulated in ***Table 4***.

Table 4: Modularity features of Cisco routers [29-34]

Models	**Cisco 3945E**	**Cisco 3925E**	**Cisco 3945**	**Cisco 3925**	**Cisco 2901**	**Cisco 2911**	**Cisco 2921**	**Cisco 2951**	**Cisco 1941**	**Cisco 1841**
Total onboard WAN or LAN 10/100/1000 ports	4	4	3	3	2	3	3	3	2	2
Cisco Service Modules	4	2	4	2	0	1	1	2	0	0
Cisco Internal Services Module (ISM)	0	0	1	1	1	1	1	1	1	0
Cisco (EHWIC) card	3	3	4	4	4	4	4	4	2	2

Table 4 gives the number and nature of the ports, Cisco Service Modules, Cisco Internal Service Modules and the EHWIC cards that differs among the different models of Cisco series routers of 2900, 3900, 1941 and 1841.

2.6.1.6 Cisco 7200

It was introduced in the market in the year 2009.Cisco 7500 was introduced in the market in the year 2010. This consists of Cisco 7505, Cisco 7507, and Cisco 7513 routers [35]. The information for these different models of 7500 series is shown. ***Table 5*** presents the factors that make the different models of Cisco 7200 series and 7500 different [36].

Table 5: Modularity features of Cisco routers [34, 35, and 36]

Models	Cisco 7505	Cisco 7507	Cisco 7513
Configurable interface slots	4	5	11
Gigabit Ethernet ports	1	2	2
Fast Ethernet (FX) ports	16	20	44

Table 5 shows the configurable interface slots, the number of Gigabit Ethernet ports and fast Ethernet ports that are present in Cisco 7200 series.

2.6.2 Juniper Routers

Here the most commonly available series of the Juniper routers are discussed. Among those the most popular ones are J, M, MX and E Series.

2.6.2.1 J Series

This series includes J2320, J2350, J4350, and J6350 routers. There are four on-board Gigabit Ethernet ports and expandable WAN and LAN interfaces via modules including the Gigabit Ethernet on J2320, J2350, J4350 and J6350. It also supports different range of interfaces supporting Serial, T1/E1, FE, DS3/E3, ISDN and others. More LAN and WAN interfaces can be added by using appropriate Physical Interface modules (PIMs) or Enhanced PIMs [37].

Table 6: Modularity features of Juniper J Series routers [37]

J Series	Gigabit Ethernet Ports	Physical Interface Modules(PIM)	Enhanced PIMs
J2320	4	3	no
J2350	4	5	no
J4350	4	4	2
J6350	4	2	4

Table 6 gives the information about the J series router. The main modularity features of these models are different Ethernet ports, physical Interface Modules and Enhanced PIMs.

2.6.2.2 M Series

In this series of Juniper routers M20, M5, M10, M160 routers are taken into consideration. Flexible PIC Concentrators numbered from FPC0 to FPC7 are present in the routers where physical interface cards can be installed [38, 39]. There are different modularity features of this series and among them the FPC slots is also one of the main factors. So the number of FPC slots present and the capacity per slots are shown in ***Table 7.***

Table 7: Modularity features of Juniper M Series routers [38,39]

Routers	M7I	M10	M40E	M120	M320
FPC Slots	1	2	8	4	8
Throughput per slots	4Gbps	4Gbps	3,2Gbps	10Gbps	20Gbps

2.6.2.3 MX Series

Key components of these MX Series router are the Dense Port Concentrators (DPCs), Modular Port Concentrators (MPCs), the Routing Engine, and the Switch Control Board (SCB). The DPCs are optimized for Ethernet density and are capable of supporting up to 40 Gigabit Ethernet or four 10 Gigabit Ethernet ports. The DPC assembly combines packet forwarding and Ethernet interfaces on a single board, with 40Gbps Packet Forwarding Engines (PFEs) [40,41]. The DPCs interface with the power supplies and SCBs. Modular Port Concentrators are especially for the flexibility purposes of modular interfaces. The Routing Engine provides control plane functions and runs Junos software whereas the SCB on and off cards, controls clocking, resets and monitors controls systems functions, including fan speed, board power status etc.

Table 8: Modularity features of Juniper MX Series routers [41,40, 42]

Router	MX80	MX240	MX480	MX960
DPC or MPCs per chassis	2 MICs no DPC/MPC	2 or 3	6	11 or 12
Chassis per rack	24	9	6	3

In this series, the DPC or MPC present in chassis affects the overall performance of the routers. So ***Table 8*** gives the available information of these series devices.

2.6.2.4 E Series

The E120 broadband services router is a high-performance router optimized for small to medium-sized points of presence. It has a 120Gbps switch fabric and hosts up to six line modules that support OC3/STM1 through OC48c/STM16 and 10 Gigabit Ethernet rates [43 ,44]. On the other hand E320 isa high-performance router designed for large points of presence. This also supports a 100Gbps or a 320Gbps switch fabric and hosts up to 12 line modules that support OC3/STM1 through OC48c/STM16 and 10 Gigabit Ethernet interfaces [45, 46].

2.6.3 Dlink Routers

Dlink routers are also the commonly available routers in the market. Here, we have discussed about different series of Dlink routers such as DAP, DI and DIR .The main components why Dlink series routers differ among themselves are the number of fixed ports, smart interface card slots and the network module slots present in them. These differing factors of different Dlink routers are shown in ***Table 9***.

Table 9: Modularity features of Dlink routers [47-52]

Model Name	Port Interfaces	Smart Interface Card, SIC slots	Network Module Slots
DAP-1353	1 10/100/1000 Gigabit Ethernet ports	3	2
DI-1721	1 10/100Mbps Fast Ethernet port and 1 10Mbps Ethernet port	1	2
DAP-1522	4 Gigabit Ethernet Ports	2	2
DIR 655	4 Gigabit Ethernet Ports	4	3
DI-624	4 10/100Mbps Fast Ethernet port	4	2

2.6.4 HP Routers

Different models of HP routers are released in the market. In this category of routers we have different models such as JF284A, JF233A JF803A, JF816A, JF802A, JE468A, J8752A, J8753A routers.

Table 10: Modularity features of HProuters [53,54,55]

Model Name	Port Configuration	Smart Interface Card, SIC slots	Multifunction Interface Module (MIM) slots
JF284A	2 10Base-T/100Base-TX/1000Base-T Ethernet ports	4	2
JF233A	2 10BASE-T, 100BASE-TX Ethernet ports	4	1
JF803A	2 1000BASE-T Gigabit Ethernet ports	4	4
JF816A	2 10BASE-T 100BASE-TX Ethernet ports	2	1
JF802A	2 10Base-T/100Base-TX/1000Base-T Gigabit Ethernet ports	4	2
JE468A	1 10Base-T,100Base-TX Ethernet ports	2	1
J8752A	2 10Base-T,100Base-TX Ethernet ports	1	1

The HP routers are different among each other due to different port configuration and different interface modules and card slots present in them. ***Table 10*** gives the detailed information about those factors of different models of HP routers.

2.6.5 Brocade Routers

Brocade routers are popular in the market these days. MLX series products of these Brocade routers are mostly used and provide 100 Gigabit Ethernet (GbE), 10GbE, and 1GbE wire-speed density, MPLS, rich IPv4, and IPv6.

Table 11: Modularity features of Brocade routers [56-58]

Features	**MLXe-4**	**MLX-4**	**MLXe-8**	**MLX-8**	**MLXe-16**	**MLX-16**	**MLXe-32**	**MLX-32**
Interface slots	4	4	8	8	16	16	32	32
Maximum 100 GbE ports	4	2	8	4	16	8	32	16
Maximum 10 GbE ports	32	32	64	64	128	128	256	256
Maximum 1 GbE ports	192	192	384	384	768	768	1536	1536

Table 11 presents the port and interface features of different series of Brocade routers. These are primarily the factors that are different in almost all the series of these routers.

3. Ethernet Switching

This chapter gives the introduction of Ethernet, Ethernet frame addressing, mapping of IP with Ethernet and MAC addresses. It also presents the detailed information of switches such as operation of switches, vendors of switches and features of different series of switches regarding different vendors.

3.1 Ethernet

It is a physical protocol that is used in most offices and many industrial networking environments. It is designed to provide more options in high-speed network connectivity and internet access. So Ethernet is a universal communication protocol standard that is used for local area networks. It defines the cable type and signal processing methods used for LANs. It has developed from a single wire broadcast technology to a star based switched technology and also supports larger bandwidth at rapidly decreasing costs [59]. The scope of the Ethernet was originally limited to only 10 Mbps interfaces but has now expanded to cover a wide range of rates. Ethernet technology is now global, with more than 500 million ports deployed worldwide [59]. It is also noticed that more than 85% of all installed network connections and more than 95% of all Local Area Networks (LANs) are Ethernet based [60]. This has made it the most widely deployed type of network today. The emergence of IP as the most dominant internetworking protocol made Ethernet technology to break out of the LAN environment and become even more prevalent. It was estimated in 2004 that IP packets will carry more than 90% of all traffic, including voice, data and video [60]. This is primarily due to Ethernet, because it is a packet-based network which is optimized to carry IP traffic. The most common forms of Ethernet used are 10BASE-T, 100BASE-TX, and 1000BASE-T. All of these three utilize twisted pair cables and 8P8C modular connectors and run at 10 Mbit/s, 100 Mbit/s, and 1 Gbit/s, respectively.

Ethernet is a universal communication protocol standard that is used for local area networks. It defines the cable type and signal processing methods used for LANs. The OSI layer 2 i.e. the data link layer associated with it is basically divided into two sub layers the Logical Link Control (LLC) and the Medium Access Control (MAC) layer. The LLC layer transitions up to the network layer and allows part of the data link layer to function independently with the other technologies. It provides the services by effectively with the network layer protocols that are above it and also with the MAC and layer 1 technology below it. The MAC layer deals with the physical media access and IEEE 802.3 MAC specifications define MAC addresses that identify uniquely multiple devices at the data link layer [61]. This layer also maintains a table of MAC addresses of devices. Communication packets flowing through Ethernet are commonly referred to as Ethernet frames. The bits that are transmitted over the Ethernet are organized into the frames. The basic structure of the Ethernet frame is shown below:

Table 12: Ethernet frame structure showing field length in bytes

Preamble(8 bytes)	Destination Address(6 bytes)	Source Address(6 bytes)	Type(2 bytes)	Data (46-1500 bytes)	FCS(4 bytes)

The fields that are in the MAC layer of the Ethernet frame have different significance. Preamble is of 8 bytes and is used to synchronize the signals of the communicating computers [62]. The destination MAC address is a field containing the MAC address of the computer the frames will be sent and is of 6 bytes. The source MAC address is the field containing the MAC address of computer sending the Ethernet frames and is also of 6 bytes. The type field of 2 bytes contains the specific code that identifies the network layer protocol and also specifies the length of the data field. The data field of 46-1500 bytes is the actual data to be transmitted over the Ethernet. The last field is the FCS of 4 bytes which refers to Frame Check Sequence and includes a checking mechanism for ensuring that the packet of data has been sent without corruption.

3.2 Ethernet Frame Addressing

There are three ways of sending the Ethernet frames. First is the unicast in which an Ethernet frame is sent by specifying the destination MAC address of the device. Other is the broadcast where a frame is send from an address to all other addresses. Third one is multicast in which the information is send to a specific group of devices or clients.

3.2.1 MAC Addresses

Each device on the LAN must have a unique MAC address to participate in the network. This address is also used to identify the specific devices in the network. So it is a hardware address that uniquely identifies each node of the network. MAC address is a necessary element for the operation of the switches. The MAC Addresses is of total 48 bits [63]. It takes the form of six pairs of hexadecimal digits e.g. 00:1F:33:69: BC: 14 where the first 3 pairs of digits identify the manufacturers name and the other three pairs are specific to the devices but can also be considered as a serial number of sorts. As in the figure we can see that there are two components of the 48 bit Ethernet MAC address. The OUI represents the manufactures of the NIC cards and the OUI numbers are regulated by the IEEE [61]. Within the OUI there are 2 bits that have the meaning only when used in the destination address. Broadcast bit refers to the receiving interface that the frame is destined to and the local bit is used when the universally unique address is modified. The 24 bit vendor assigned identifies the Ethernet hardware.

3.2.2 Mapping of IP with Ethernet

When a TCP connection needs to send a packet of data to another device over the Ethernet; it passes the packet to IP for transmission. Then the IP handles the interface to Ethernet and ensures that the packet gets transmitted to the Ethernet network of the destined device. IP runs over Ethernet or over other variety of LAN or WAN technologies. There is an Address Resolution Protocol (ARP) in the network layer which is used to map Ethernet addresses to IP addresses and maintain mapping tables in each device on the network. The ARP is a protocol used by the Internet Protocol (IP) specifically IPv4, to map the network addresses of IP to the hardware addresses which are used by a Data Link Protocol. An Ethernet network uses two hardware addresses which identify the source and destination of each frame that are sent by the Ethernet. The destination address may also identify a broadcast packet. The hardware address is also known as the MAC addresses [64].

3.3 Switches

Switches are the electronic devices that operate at the layer 2 i.e. the data link layer and sometimes in the layer 3 i.e. network layer of the OSI reference model. Like the routers, switches are also box like equipment that joins multiple computers together within one local area network [65]. Switches inspect data packets as they are received, determine the source and destination device of each packet, and forward them appropriately. These are only concerned with moving data across the physical links in the network. So, the switches looks at each data unit and determines from the physical address which device it is intended for and switches towards that device. Here the switches use the destination medium access control MAC address to know where to direct the message [64]. Every Ethernet frame contains a source and destination address. Switches operate by examining the hardware addresses in those Ethernet frame.

a) Cisco switch

b) Juniper switch

Figure 8: Examples of Switches [67]

The switch knows the MAC addresses of the end nodes by examining the source hardware address of each packet received on a port. After the frame is received it looks at the destination address available in the MAC table also known as forwarding table and finds the exit interface. It then adds the address and port on which the packet was received to the MAC table if the address has not been entered in the MAC table [66, 64]. Finally loop avoidance method is used when multiple connections between the switches are created. Now, the table contains all the MAC addresses of the devices that are connected to the switch's ports and the port number where each address was learned. When a switch receives a packet with a destination address that is in the MAC table then it determines the destination port and forwards the packet to the appropriate port. But, if a packet is received whose destination address is not in the forwarding table then it floods the packet to all the ports on the switch. On the other hand if the switch receives a packet with a destination address that is on the same port on which the packet was received, it discards the packet without forwarding it to other ports [65]. This is because as both the source node and the destination node for the packet are located on the same port, there is no reason for the switch to forward the packet.

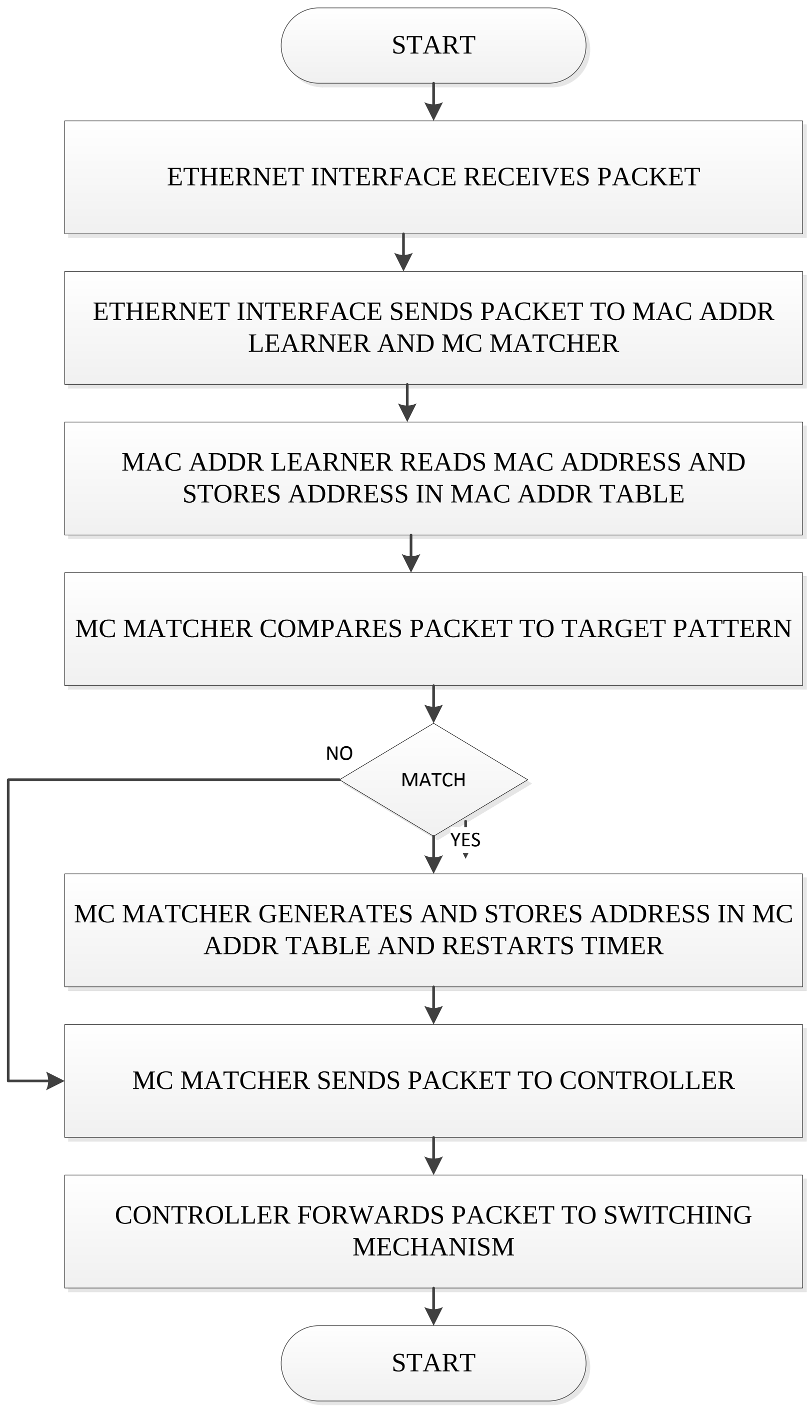

Figure 9: Switching process [67]

Figure 9 shows the general switching process involved after the Ethernet receives the data packets.

3.4 Types and Vendors of Switches

There are basically three types of switches that are available in the market. The first type is the fixed configuration switches where we cannot add features or options to the switch other than those that originally came with the switches. The other type is the modular switches which gives flexible configuration. It allows for the installation of different modular line cards. The third one is the stackable type of switches which allows for the interconnection of the switches. This stackable switch operates effectively as a one large switch [66]. Depending upon the switching capacity type of switch, number of ports and power requirements there are many vendors of switches available in the market such as the Cisco, Juniper, Brocade, D-link, HP, Avaya, Linksys etc. The market consumption of the switches depends upon the performance and most importantly the price of the device.

3.4.1 Cisco Switches

Here we have dealt with the different types of switches. The most common types of switches that are used for analysis purpose are ESW 500 series switches, SFE2000P switch, Cisco catalyst switches that include 2960-S Series, 2900 series switches and other switches [68, 69]. These are designed to meet the needs of a wide range of customers—from small to medium businesses, right up to large enterprise networks and service providers. These switches provide high performance, scalability, manageability, and many other intelligent features. Cisco catalyst switches can be physically described by one of two devices, fixed-configuration switch or Chassis-based switch. The fixed-configuration switch consists of fixed number or ports, an internal switch processor that is contained within a fixed chassis. The major advantages of these fixed-configuration switches are low cost and ease of deployment. On the other hand its disadvantages are a lack of flexibility and limited degree of modularity in that they include modular slots that can be populated by variety of different modules. The chassis-based switch provides a chassis as a starting point, after that various components of the switch can be added as required. Chassis-based switches provide slots, which support various types of modules. Its advantages include high performance, flexibility and simplified management. The major disadvantage of chassis-based switches is the high cost involved. [70,69,71].

This switches offers two classes of line cards one is classic and other is E-Series. The classic line cards provide 6 gigabits of switching capacity per slot but the E-Series line cards provide increased switching capacity per slot. Two types of E-Series line cards are available based on the per-slot switching capacity. E-Series line cards which are numbered 47xx operate at 48 gigabits per slot, while cards numbered 46xx operate at 24 gigabits per slot [72].

Table 13: Modularity features of Cisco switches [69-72]

Line cards	Number of ports	Gigabit Ethernet	Capacity per slot
WS-X4712-SFP+E	12	10	48Gbps
WS-X4606-X2-E	6	10	24Gbps
WS-X4624-SFP-E	24	1	24Gbps
WS-X4612-SFP-E	12	1	12Gbps

Line cards those are available for Cisco Catalyst 4500 series switches also represents different models of these switches. ***Table 13*** gives the information about the number, nature and the capacity of the ports that have a crucial influence in the overall performance of these devices.

3.4.1.2 Cisco ESW 500 Series

This series has 520-8P, 520-24, 520-24P, 520-48, 520-48P which was introduced in the market in the year 2004 [73].These series switches have easy integration and simple graphical user interfaces for easier configuration, management, and troubleshooting. Choice of configuration and management tools with. These series of switches offers Fast Ethernet and Gigabit Ethernet, connectivity Power over Ethernet (PoE) on up to 48 ports of Fast Ethernet and 24 ports of Gigabit Ethernet. Small Form-Factor Pluggable (SFP) expansion slots are available for the flexible network design. These series of switches has Gigabit Ethernet speeds to deliver optimal network performance.

Table 14: Modularity features of Cisco ESW switches [73]

Name	Number of ports	port type
ESW-520-48	48	10/100BaseTX 10/100/1000BaseT(2 ports shared)
ESW-540-24P	24	10/100/1000BaseT
ESW-520-24	24	10/100BaseTX 10/100/1000BaseT(2 ports shared)
ESW-540-8P	8	10/100/1000BaseT
ESW-540-24	24	10/100/1000BaseT

The port number and the port type have an important influence on the performance of these devices which is presented in ***Table 14***.

3.4.1.3 SFE2000P

This is a 24 port stackable switch which was introduced in the market in 2002. This offers Fast Ethernet connectivity power over Ethernet. It has 2 Gigabit SFP [74].

3.4.2 Juniper Switches

The most available juniper model switches are the EX2200, EX2500, EX3200, EX3300, EX4200, EX4500 series. These switches were available in the market between the years 2006 to 2011 period. Of the switches of this series, the EX 3200 series has fixed-configuration platforms, the EX 4200 series has Virtual Chassis technology, and the EX 8200 series features a modular chassis. Virtual Chassis technology allows various EX 4200 models to be mixed in a single device or form that supports up to 480 10/100/1000BASE-T or 240 100BASE-FX/1000BASE-Xports and an additional 40GbE or 20 10GbE uplink ports. EX 8200 series switches features modular chassis which accepts a variety of plug-in modules of different type needed for expansion. The EX 4200 series switches can deploy a single 24-port or 48-port switch initially. As the requirements grow, Juniper Networks Virtual Chassis technology allows up to 10 EX 4200 series switches to be interconnected to form a single device, over a 128Gpbs backplane in case required for expanding network environments. [75, 76].

Table 15: Modularity features of Juniper EX series switches [75-77]

Model name	Port Interface	PoE ports
EX 3200-24T	24- 10/100/1000 Ethernet ports	8
EX 3200-24P	24- 10/100/1000 Ethernet ports	24
EX 3200-48T	48- 10/100/1000 Ethernet ports	8
EX 3200-48P	48 10/100/1000 Ethernet ports	48
EX 4200-24T	24- 10/100/1000 ports	8
EX 4200-24P	24-port 10/100/1000 ports	24
EX 4200-48T	48-port 10/100/1000 ports	8
EX 4200-48P	48-port 10/100/1000 ports	48

Table 16: Modularity features of Juniper EX 8200 series switches [76,78]

Model name	Port interfaces	SFP/ XFP ports
EX 8200-8XS	8 10 Gigabit Ethernet port	2 fixed 1000/10000 SFP ports
EX 8200-48F	48 100/1000 Mbps port	1 fixed 1000/10000 SFP ports
EX 8200-48T	48 10/100/1000 Mbps port	-

Tables 15 and ***16*** presents the information about the port interfaces and the present of PoE ports that are available in these switches. The system power with and without the PoE ports are also given.

3.4.3 HP Switches

There are mostly 3 series of switches that are manufactured by the HP. They are A series, E series and V series switches.

Table 17: Modularity features of HP 5830 Switch series switches [79-82]

Model name	Port interfaces	SFP ports
HP 5830AF-48G(JC691A)	48 10/100/1000 ports 10BASE-T, 100BASE-TX, 1000BASE-T	2 fixed 1000/10000 SFP ports
HP 5830AF-96G (JC694A)	96 10/100/1000 ports 10BASE-T, 100BASE-TX, 1000BASE-T	10 fixed 1000/10000 SFP ports
HP 5920AF-24XG	24 1000/10000 Ethernet ports	24 fixed 1000/10000 SFP ports
HP E2910-24G al 24	24 x 10/100/1000 Ethernet ports	4 x shared SFP
J9080A	22 10/100 ports and 2 supporting 10/100/1000 Ethernet ports	-
J9080A	7 10/100 ports and 1 supporting 10/100/1000 Ethernet port	-

Table 17 presents the information of the port interfaces and SFP ports along with the switching capacity of different models of HP switches.

Table 18: Modularity features of H3C S7500E series switches [82,83,84]

Model name	Slots available	Service slots	Switching capacity (Gbps)
S7510E	12	10	1152
S7506E	8	6	768
S7506E-V	8	6	768
S7506E-S	8	6	384
S7503E	5	3	480
S7503E-S	3	2	288
S7502E	4	2	192

In ***Table 18*** the different model names of the HP switches, their available number of service slots are shown. Their switching capacity is also presented.

3.4.4 Brocade Switches

Brocade switches are the foundation for high-performance connectivity in storage, IP and converged network environments. These are highly reliable, scalable, and are designed for a wide range of environments. These are the switches with are gaining popularity in the recent years. The most common models of these switches are the FCX and the ICX models.

Table 19: Modularity features of Brocade switches [85,86]

Series name	FCX 624	FCX 648	ICX 6610-24	ICX 6610-48
10/100/1000 Mbps RJ-45 ports	24	48	24	48
10 Gigabit Ethernet SFP+ ports	4	4	8	8
1000 Mbps combo ports	4	4	-	-

In ***Table 19*** the description of the nature and the types of port interfaces are described which are different for different models.

3.4.5 Dlink Switches

Different models of Dlink switches are available such as DWS, DGS DES series. These switches provide high bandwidth, converged architectures, guaranteed interoperability, robust security and future compatibility. The description of available series is done in ***Table 20.***

Table 20: Modularity features of Dlink switches [87-94]

Model name	Port Interfaces	SFP/ XFP ports	Switching fabric
DWS 3227	24 10/100/1000 Ports	4 Combo SFP Ports, 1 Fixed XFP interface	120Gbps
DGS 3627	24 10/100/1000 Ports	4 shared SFP and 3 Expansion Slot	-
DGS 3200-10	8 10/100/1000 Ports	2 combo Gigabit SFP	192Gbps
DGS 1224T	24 10/100/1000 Ports	3 shared SFP ports	-
DES 3550	48 10/100Mbps ports	2 10/100/1000Mbps SFP slots	13.6Gbps

Table 20 gives different models of Dlink switches with their port interfaces and types of Ethernet. It also presents the switching capacity of these devices.

4. Analysis

In this chapter discussions and analysis of energy consumption of routers and switches across different manufacturers in different years are done. Also previous works related to this topic are also mentioned. Comparison of routers and switches of same manufacturer in same year are also made. Furthermore, comparison among the vendors is done to find the least power consuming router and switch vendor.

4.1 Discussion of Energy Consumption of Routers and Switches

In the ICT field, the communication network is a major contributor to the total power consumption [5]. Routers and switches being integral part of it, the energy consumption of these devices is of greater issue these days. Generally routers and switches are small box like piece of equipment containing different ports that can connect multiple computers and networks. But they differ in the inner working that makes them consume different power and vary in the performance. The port configurations, physical size, presence of different modules and features are the key issues of it. Different vendors of switches and routers are being developed and released. These differ among themselves in data rate, power consumption and the amount of heat dissipation and other several factors. Different routers and switches such an Avaya, Dell, D-Link, Cisco Systems, HP, Juniper Networks, Telco Systems, Brocade, and Nortel etc. are in use. Due to the increasing demand of ICT equipment, new vendors are introduced regularly.

4.2 Previous Works

There are few articles that deal especially with the power consumption of the devices and moreover to our knowledge there is no thorough compilation of data across different vendors and manufactures of routers and switches [95]. Much work has not been done regarding the energy consumption trend, comparison of vendors and comparison done on routers and switches of similar vendor. Some of the papers are useful in gaining valuable information. Networking devices such as routers and switches are found throughout the world in data centers, offices, homes and other places. Energy used by this ICT equipment represents about 8% of the electrical power in the EU [96]. It is about 2% of the green –house gas emissions. This energy used by the ICT equipment might grow to over 10% of electrical power by 2020 if measures are not taken to reduce the power consumption [95]. The ubiquity of these devices and their propensity to consume large amount of power with increasing data rate are the reasons for designing power aware and energy efficient future systems. Now is the best time to phase out network devices, e.g. servers, routers, switches, etc. that consumes high energy and replace them by their more energy efficient counterparts [97].

In this section, the information regarding the energy related issues of the routers and switches are drawn from the papers [4], [98]. The ***Figures 10*** and ***11*** are taken from the same papers.

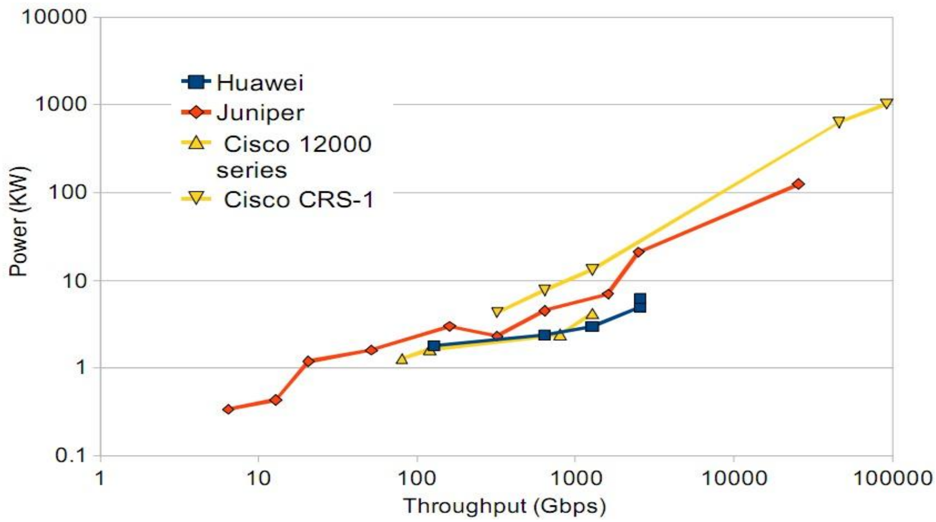

Figure 10: **Router power consumption related to their aggregated capacity [98]**

Figure 10 shows the capacities and the power required by different vendors of routers available in the market. It especially focuses on some of the major router vendors such as the Juniper, Huawei, and Cisco. It can be analyzed from the figure that the power consumption scales are almost linear with their total aggregate throughput. Also the power consumption figures are consistent across the different vendors. It shows a general trend of increment in the power as the throughput of the different series of routers increases.

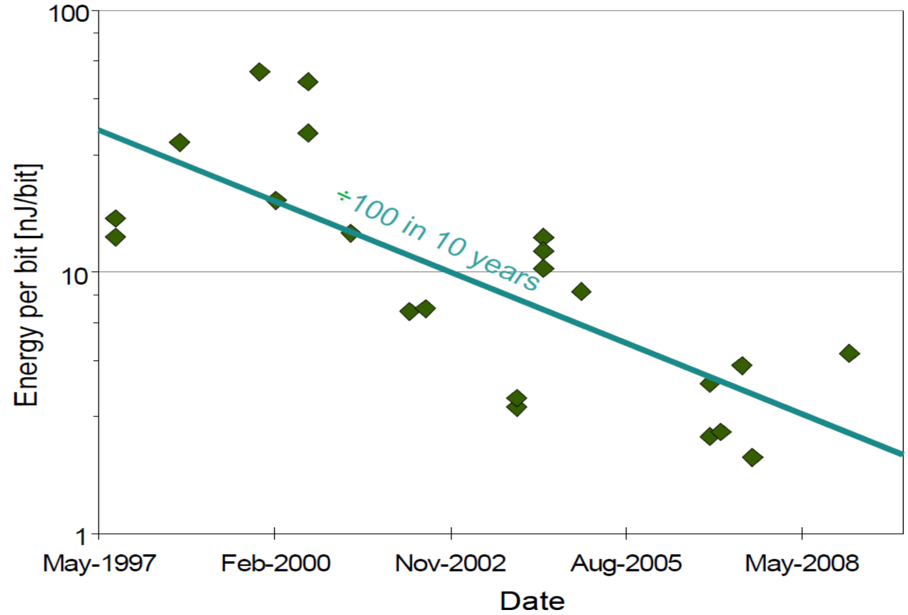

Figure 11: Evolution of energy scale with time [98]

In ***Figure 11***, it is shown how the energy scale is changing as the evolution of the time. It shows the aggregate capacity of the top core routers as the function of their release dates in different time periods. The energy scale is measured in terms of the energy per bit required in case of those routers. The energy per bit (measured in nJ/bit) is plotted. From the plot, it can be concluded that there is a general trend of decrement of energy consumption per bit of the routers than in the previous years. The value is almost decreased by 100 times in the time span of 10 years. So, the newer routers consumed less energy than the older ones. Thus, it can be interpreted that the manufacturers are being more aware of energy consumption and beginning to focus on developing power and energy efficient routers and switches in the recent years.

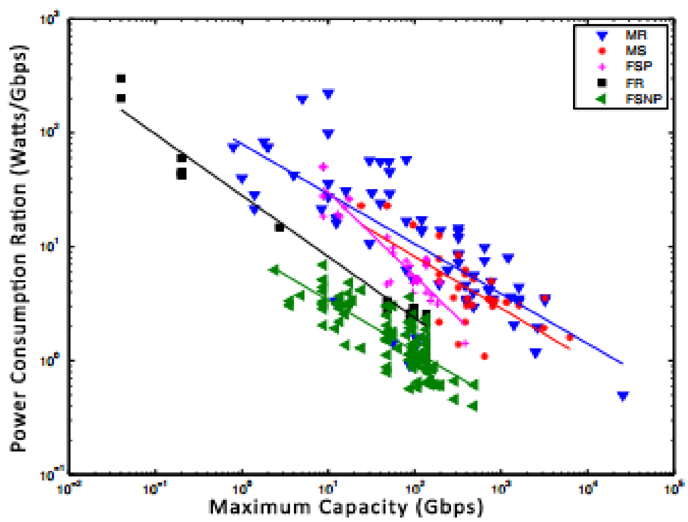

Figure 12: Power consumption ratio of routers and switches [6]

Figure 12 shows the power over the capacity ratio which is in watts/Gbps is plotted against the maximum capacity. In this related paper linear regressions of each group of data are shown to obtain a more precise idea on the power consumptions trend of routers and switches .The axis are given in the logarithmic scale and that there is a large diversity in power consumption values in same level of capacity in both routers and switches. Also, it presents that the switches have a significant lower consumption than the routers of the same capacity.

4.3 Analysis

This is the main part of our research and is mainly divided into three parts. In first and second part it deals with routers and switches respectively and finally comparison of the routers and switches is done in other part. Here, routers and switches of different manufacturers are collected and are mentioned in the literature part. Devices are found mainly with three types, one under 1GbE, one with multiple 1GbE ports and third one with multiple 10GbE ports. Most of the devices both in case of routers and switches were with multiple 1GbE ports so the analysis and the graphs are done for these types of devices. In case of Brocade networks, data related to the high speed devices i.e. multiple 10GbE ports or higher are shown and compared with the devices with multiple 1GbE ports.

Maximum, minimum and the average values of energy per megabit required are plotted for the devices which are released during the same period of time. Few of the manufactures made the release date of the products available and also little information about the maximum power and typical power consumption has been available in the datasheets. The figures are drawn from the data available in Appendixes A and B.

4.4 Routers

Here the energy consumption of different vendors of routers such as D-link, Cisco, Juniper, Avaya, HP and Brocade are analyzed. Routers are, in general, used to connect to the outside networks and provides with certain services such as Multiprotocol Label Switching (MPLS), Quality of Service (QoS), Virtual Private Network (VPN), security, multicasting, reliability, availability and others. MPLS is a technology for forwarding data packet with improved forwarding speed of routers by using labels to make data forwarding decisions. Security features such as firewall, detection and protection against attack and filtering capabilities also made the routers consume more power. Apart from the security features the important factor that make the routers differ among themselves in the capacity and the power consumption are the type of available and supported network interfaces or ports. These includes Ethernet, Gigabit Ethernet (GbE), 10-GbE, Power over Ethernet (PoE), voice/WAN interface cards (VWICs), Enhanced High-Speed WAN Interface Card (EHWIC), optical interfaces including small form-factor pluggable (SFP), 10-GbE SFP (XFP) etc. Also, the routers with compact and light weight offering a limited set of services, limited type of interfaces for connectivity and limited range of capacities consume less power than those routers which are flexible, scalable, offer more services and connectivity options. So, these are the major factors that affect the power consumption of the routers. From the analysis we can see that the routers supporting the addition of the interfaces, line cards and additional ports consume more power than the other routers and also there has been reduction in the power consumption in recent years. Description of those features, connectivity options, interfaces are mentioned in each of the individual vendors of routers and finally the graphs are shown representing the energy per megabit requirement in different years.

4.4.1 Cisco Routers

Different series of Cisco routers are taken and their power consumption along with the performance is noted. Different modularity factors of different series affecting the power consumption were also taken into account.

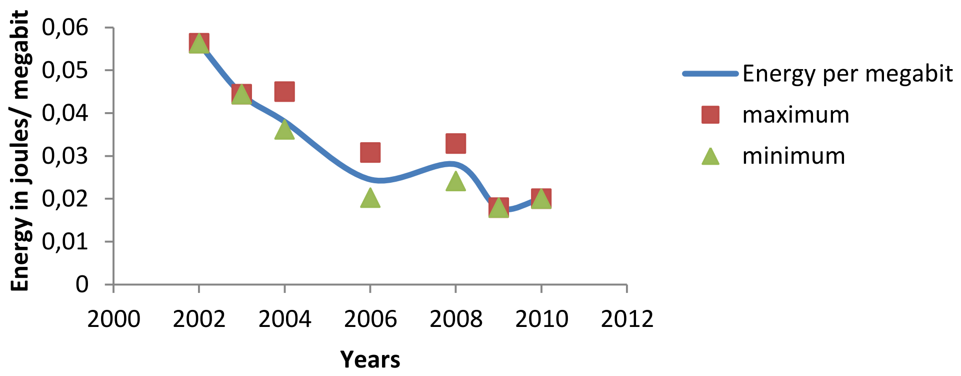

Figure 13: Energy per megabit requirement for the Cisco Routers

Figure 13 presents the energy consumption trend of different models of the Cisco routers introduced in different year. The energy per megabit line in the graph represents the average value of the devices released in the same year , whereas the maximum and the minimum represents the highest values and lowest values respectively during that year. There is a decreasing trend which means that the Cisco routers have been energy aware in developing the devices in the recent years.

4.4.2 Juniper Routers

Discussions are done in case of the J series, M series, MX series, E series and other juniper routers. Their power consumption along with the performance was evaluated.

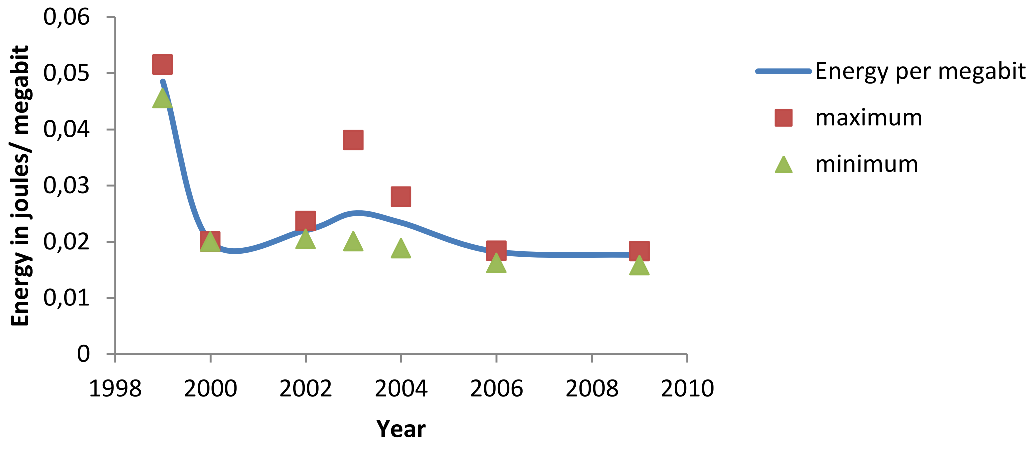

Figure 14: Energy per megabit requirement for the Juniper Routers

Figure 14 shows the energy consumption trend in different years for different models of Juniper routers. There has been a considerable decrease in the power consumption of these devices except a slight increase during the year 2002-2004. So we can agree that Juniper vendors are also energy conscious and are trying to reduce the power consumption in their latest products.

4.4.3 Dlink Routers

Different types of Dlink routers are taken into consideration for finding the general trend of the Dlink routers.

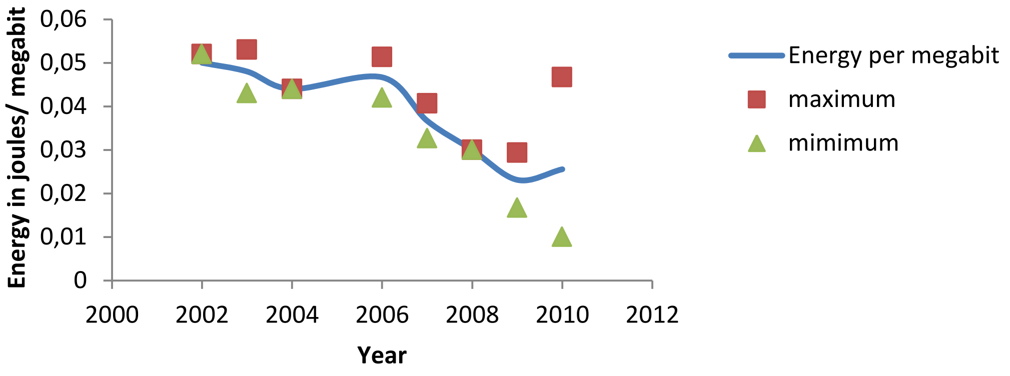

Figure 15: Energy per megabit requirement for the Dlink Routers

The graph shows the energy consumption trend of Dlink routers in different years. It shows a consistent and uniform decrease in energy per megabit requirement for Dlink routers. So we can conclude that this vendor is also being energy efficient in the recent years.

4.4.4 HP Routers

In this category of routers we have different models such as JF284A, JF233A JF803A, JF816A, JF802A, JE468A, J8752A, J8753A routers. These routers are taken in order to find an energy trend graph of these series routers.

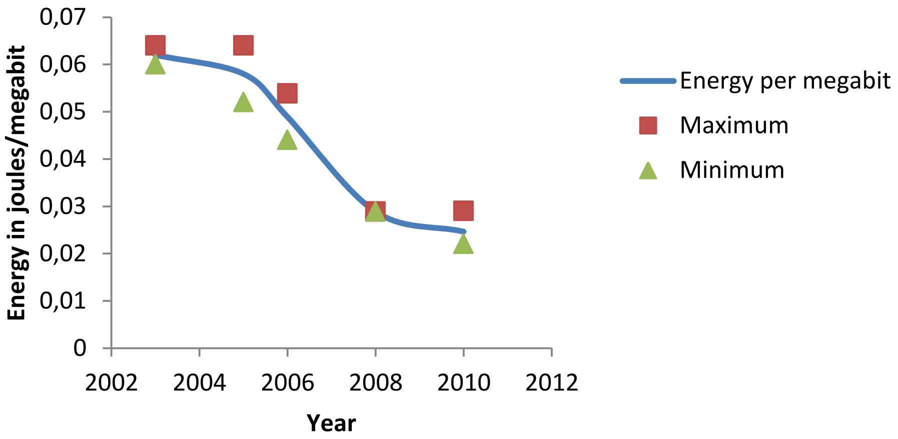

Figure 16: Energy per megabit requirement for the HP Routers

The analysis on the energy consumption trend of different models of HP routers in different years is shown in the figure above. It shows the general decreasing trend in the power consumption over the years. A slight increase during the year 2006-2008 has also been seen. Overall this vendor also has been energy efficient and conscious in the recent years.

4.4.5 Brocade Routers

Different series of Brocade routers are taken in account for the analysis purpose. Brocade routers devices with multiple 1GbE are shown along the devices with multiple 10GbE ports. The average values of energy per megabit required for both types of devices in a year are considered.

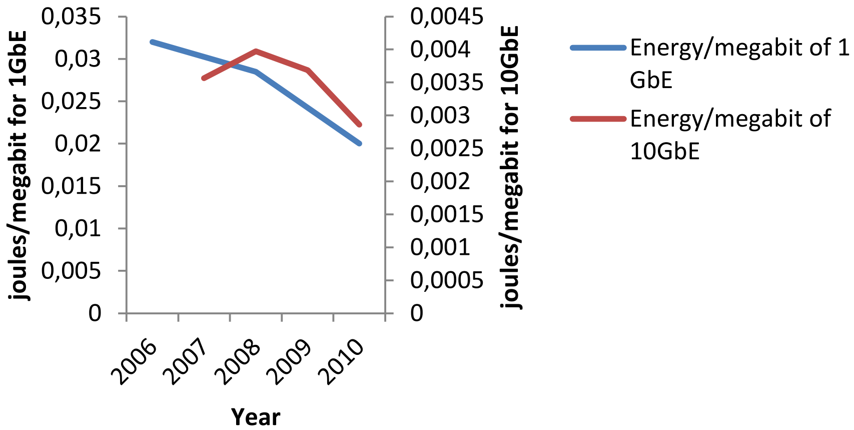

Figure 17: Energy per megabit requirement for the Brocade Routers

Figure 17 shows the energy consumption trend of Brocade routers in different years. The primary vertical axis represents the energy consumption scale for devices with 1GbE whereas the secondary vertical axis represents the 10GbE devices. The energy consumption trend for both types of devices is decreasing over the years. The value of energy consumed per megabit is less for the fast devices of 10GbE. Overall the graph is a decreasing one for both types of devices which suggests that these routers are energy efficient and conscious during the years.

4.4.6 Comparison of all Manufactures Routers

Here the comparison of all the devices with multiple 1GbE ports of different manufacturers is done. The average value of energy in joules per megabit required for different years is used for this purpose.

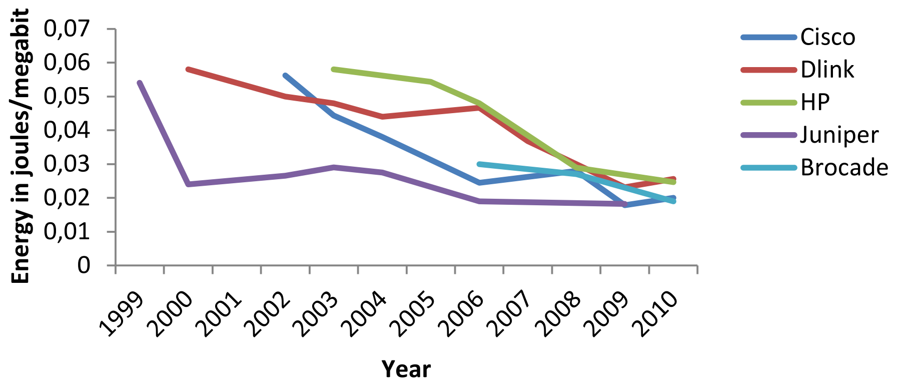

Figure 18: Energy per megabit requirement for different manufacturer routers

Figure 18 shows the energy consumption trend of different manufacturers of routers in different years. The graph shows that Juniper routers have the least energy consumption per megabit than the other vendors' devices. Apart from this, all the vendors have a decreasing trend of energy consumption except in some years. Also, the graph shows similar lesser values for all the vendors in the recent years which indicates that the vendors are moving towards designing energy efficient routers in recent years. The average values of energy in joules/megabit for all the manufacturers devices with multiple 1GbE ports are shown in ***Table 21***.

Table 21: Average Energy in Joules/megabit for different manufacturer of routers

Year	Average Energy in joules/ megabit of different manufacturer routers				
	Cisco	Dlink	HP	Juniper	Brocade
1999	-	-	-	0,054	-
2000	-	0,058	-	0,024	-
2001	-	-	-	-	-
2002	0,05625	0,05	-	0,026545	-
2003	0,044375	0,048	0,058	0,029	-
2004	0,038009	0,044	-	0,0275	-
2005	-	-	0,0543	-	-
2006	0,0245	0,046667	0,048	0,019	0,03
2007	-	0,036778	-	-	-
2008	0,028013	0,03	0,02887	-	0,027
2009	0,017857	0,02311	-	0,0182	-
2010	0,02	0,025555	0,02466	-	0,019

4.5 Switches

Here the energy consumption of different vendors of the switches such as D-link, Cisco, Juniper, Avaya, HP and Brocade are analyzed. The main factor that differentiates the power consumption of different vendors of switches is the number of ports, port configuration, Ethernet type and the PoE capabilities. It is worth mentioning that the extra power consumed by PoE equipment is not really wasted as it is used to power-up connected devices, such as video cameras, IP telephones, and wireless LAN access points, through the Ethernet cable. But certain portion of this power is dissipated in the cable. Description of those port features, interfaces are mentioned in each of the individual vendors of switches and finally the graphs are shown representing the energy per megabit requirement in different years. Looking upon the different manufactures switches we can see a general reduction in power consumption over the years as that of the routers.

4.5.1 Cisco Switches

Different series of the Cisco switches which were earlier discussed in the section 3 are considered. Their energy consumption and the performance are used for analysis purpose.

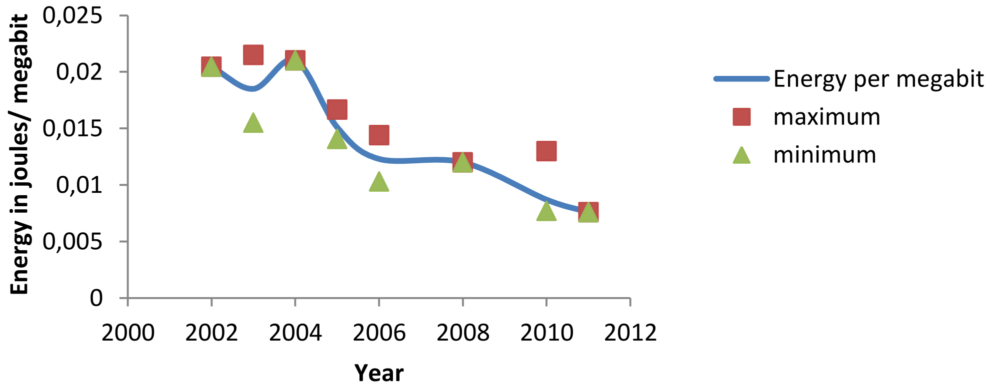

Figure 19: Energy per megabit requirement for the Cisco Switches

The analysis on the energy consumption trend of different models of Cisco switches in different years is shown in ***Figure 19***. The graph shows the deceasing trend except a slight increase during the years 2000-2002 and 2008-2009. But we can conclude that there has also been a significant effort to reduce the power consumption over the years.

4.5.2 Juniper Switches

Here the different series of Juniper switches discussed in ***Section 3*** are used for the analysis purpose.

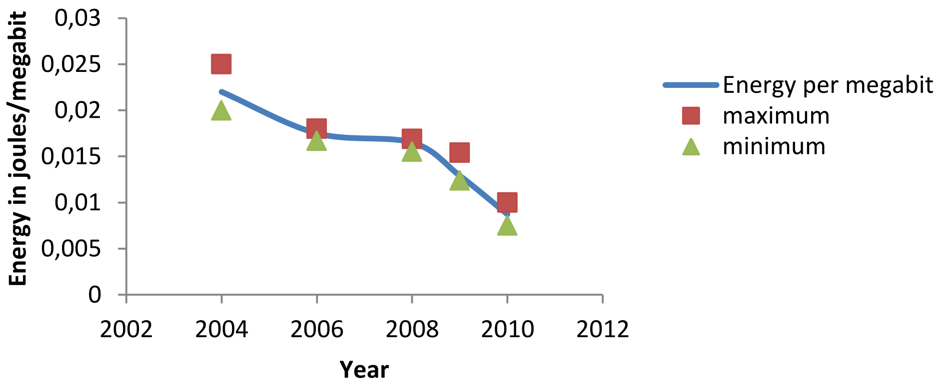

Figure 20: Energy per megabit requirement for the Juniper Switches

The graph represents the energy consumption per bit requirement for different vendors of Juniper switches in different years. The graph is a decreasing one with an exception during the period 2009-2010. The decrements in power consumption over the years indicate that Juniper switches are also being energy efficient and conscious.

4.5.3 HP Switches

There are mostly 3 series of switches that are manufactured by the HP. They are A series, E series and V series switches. So these are the ones that are taken into consideration.

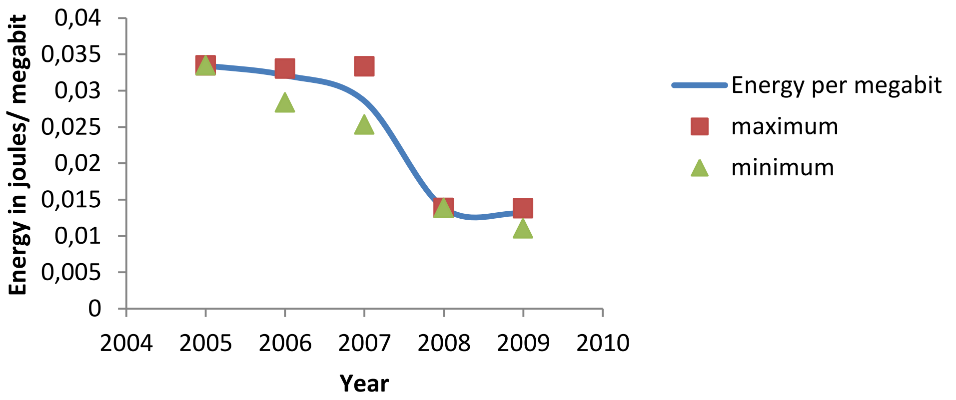

Figure 21: Energy requirement for the HP Switches

From ***Figure 21*** we can see that the power required by different models of HP switches have a decreasing trend over the years. A slight increment can be during the year 2007-2008. Overall the HP switches are concerned about the power consumption and has considerably reduced in the amount of power consumption in recent years.

4.5.4 Brocade Switches

These are the switches with are gaining popularity in the recent years. Brocade switch devices with multiple 1GbE are plotted along with the devices with multiple 10GbE ports. The average values of energy per megabit required for the devices in a certain year are considered for drawing the graphs.

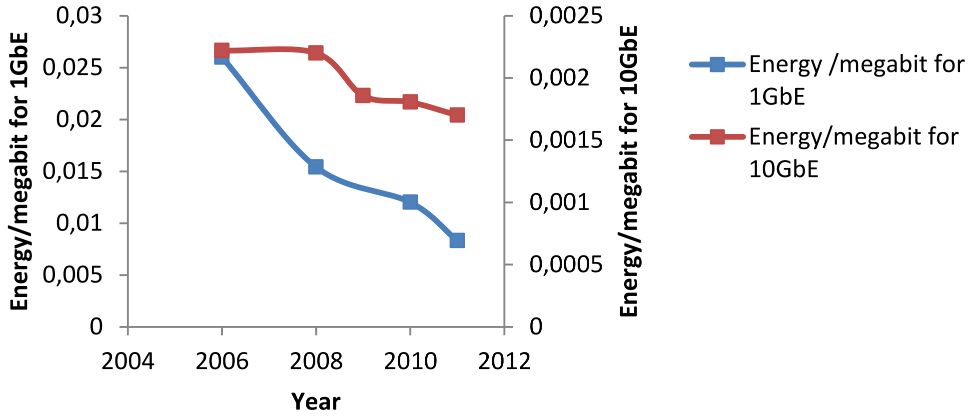

Figure 22: Energy per megabit requirement for the Brocade switches

Figure 22 shows the two different energy consumption trends of Brocade switches. The primary vertical axis represents the energy consumption scale for devices with 1GbE whereas the secondary vertical axis represents for the 10GbE devices. From the graph it is seen that the energy consumption trend for both type of devices is decreasing over the years. The value of energy consumed per megabit is less for the fast devices of 10GbE. Overall the graph is a decreasing one for both the devices which suggests that these switches are energy efficient and conscious during the years.

4.5.5 Dlink Switches

Different models of available Dlink switches such as DWS, DGS DES series are considered for the analysis purpose. Based on the different modularity features of the different series the power consumption differs among them.

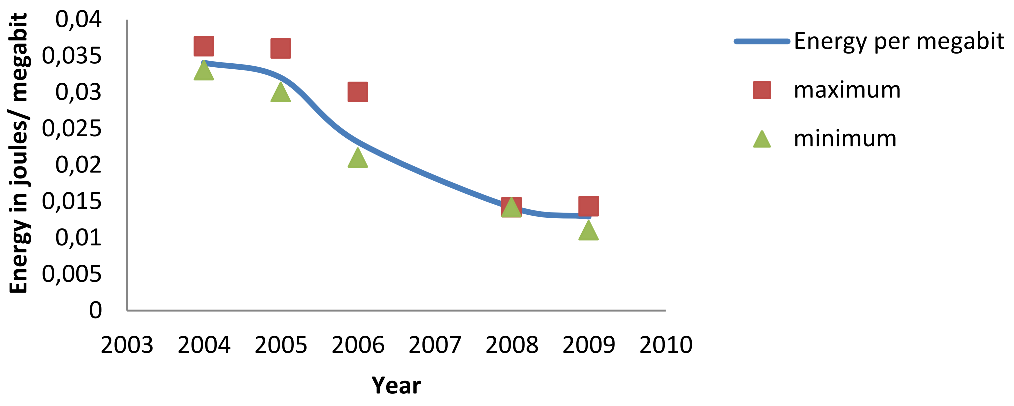

Figure 23: Energy per megabit requirement for the Dlink switches

In ***Figure 23*** we draw the energy consumption trend of different models of the Dlink switches over the years. The graph is of decreasing nature so it suggests that this vendor is being energy conscious across recent years.

4.5.6 Comparison of all Manufacturer of Switches

Here the graph is plotted taking into account the switches of different manufacturers with multiple 1GbE ports. The average values of energy per megabit required in different year is used for this purpose.

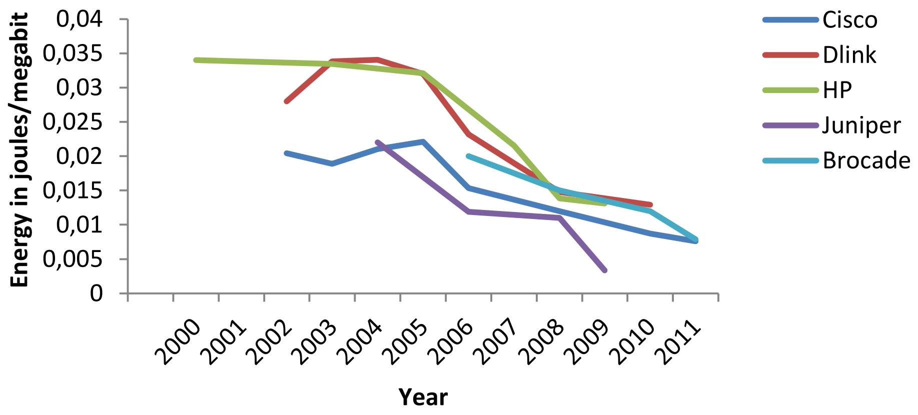

Figure 24: Energy per megabit requirement for different manufacturer switches

Figure 24 shows the energy consumption trend of different manufacturers of switches. Among all the manufacturers Juniper switches has been the least energy consuming. Almost all the vendors have the decreasing trend except in some years. Also, the graph shows closer values for all the vendors in the recent years. This shows that the vendors are moving towards designing energy efficient switches in recent years. The average values of the energy in joules/megabit for all the manufacturers devices with multiple 1GbE ports are shown in ***Table 22***.

Table 22: Average Energy in Joules/megabit for different manufacturer of switches

Year	Average Energy in joules/ megabit of different manufacturer switches				
	Cisco	**Dlink**	**HP**	**Juniper**	**Brocade**
2000	-	-	0,034	-	-
2001	-	-	-	-	-
2002	0,02045	0,028	-	-	-
2003	0,0189	0,0338	0,03345	-	-
2004	0,021022	0,03406	-	0,022	-
2005	0,0221	0,032	0,03211	-	-
2006	0,015333	0,023168	-	0,0119	0,02
2007	-	-	0,02157	-	-
2008	0,012	0,014764	0,01385	0,011	0,015
2009	-	-	0,01311	0,003353	-
2010	0,0087	0,01292	-	-	0,012
2011	0,0076	-	-	-	0,0079

4.6 IP vs Ethernet

Here the comparison of the energy consumption of the routers and switches is done. It is carried out on the routers and switches of same manufacturer released in the same year. Due to unavailability of much release dates of both routers and switches on same period there has been limited data for analysis. From the analysis, it is found out that routers provide a variety of LAN and WAN interfaces ranging from Ethernet-based (FE, Gigabit Ethernet, 10-GbE, SFP and XFP), Enhanced High-Speed WAN Interface Card (EHWIC) etc. whereas most switches are equipped with Ethernet-based interfaces only as they were mainly designed to be used in LAN environments. This can have an impact on the choice of equipment and, therefore, on overall network consumption. Routers support Multiprotocol Label Switching (MPLS), Quality of Service (QoS), and Virtual Private Network (VPN), security, multicasting, reliability, availability and other functions which are also the reason behind its more power consuming nature than the switches. Looking upon all the manufacturers routers and switches released on the same year it is clear that the switches have the less energy per bit requirement than the routers.

Different figures showing the comparison of the routers and switches of different manufactures in different years are shown below. The comparison is done for the devices with multiple 1GbE ports. In general all the comparison shows that the routers are more energy consuming than the switches of same vendors for a particular year.

4.6.1 Comparison of Cisco Routers and Switches

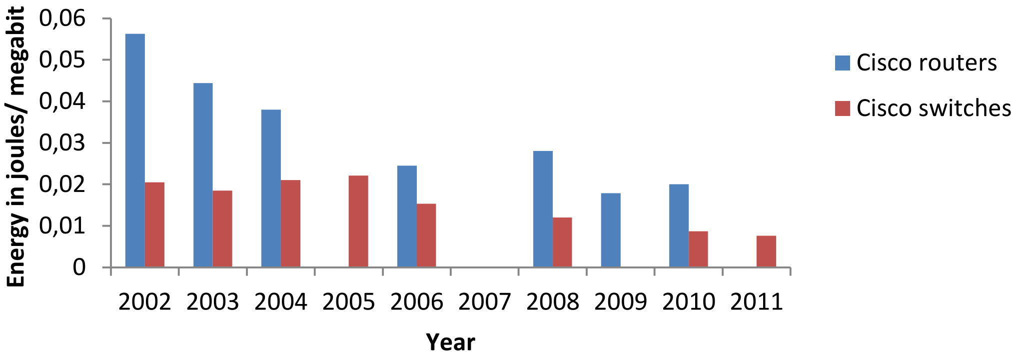

Figure 25: Energy per megabit comparison of Cisco router and switch

In ***Figure 25*** the comparison of power consumption of Cisco routers and switches released on same years are done. The diagram shows that Cisco routers consume more power than the Cisco switches over different years. The blank in some diagram is due to the unavailability of the data.

4.6.2 Comparison of HP Routers and Switches

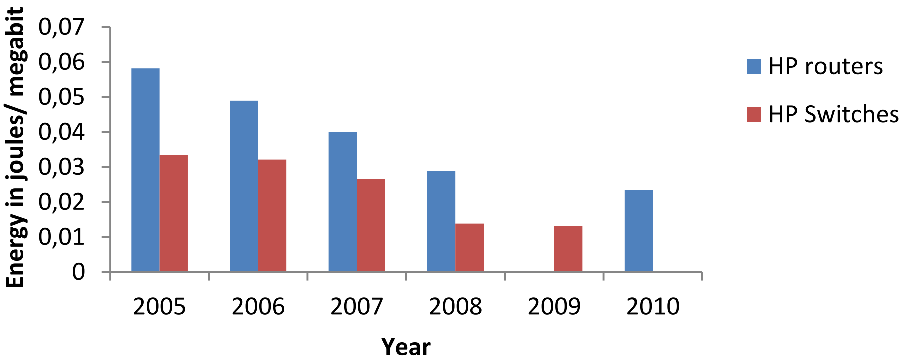

Figure 26: Energy per megabit comparison of HP router and switch

In ***Figure 26*** the comparison of power consumption of HP routers and switches released in same year are done. It shows that HP routers consume more power than the HP switches. The year without both bar diagrams indicates the unavailability of the data during that period.

4.6.3 Comparison of Dlink Routers and Switches

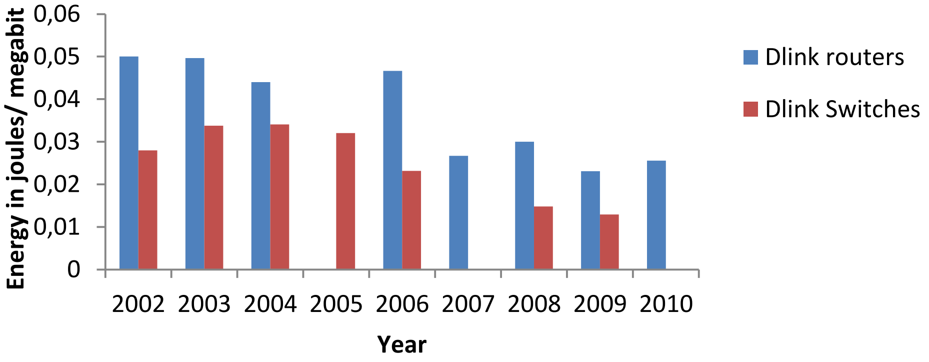

Figure 27: **Energy per megabit comparison of Dlink router and switch**

Figure 27 shows the comparison of power consumption of Dlink routers and switches that were released in same year. From the analysis we can see that the Dlink switches consume less power than the routers. The year without both bar diagrams indicates the unavailability of the data during that period.

4.6.4 Comparison of Brocade Routers and Switches

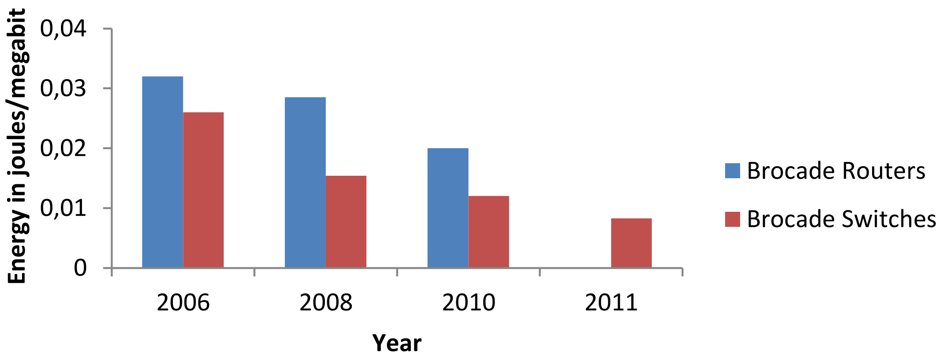

Figure 28: Energy per megabit comparison of Brocade router and switch

Figure 28 shows the comparison of power consumption of Brocade routers and switches that are available in the same year. From the analysis we can see that the Brocade switches consume less power than the Brocade routers. The year without both bar diagrams indicates the unavailability of the data during that period.

4.6.5 Comparison of Juniper Routers and Switches

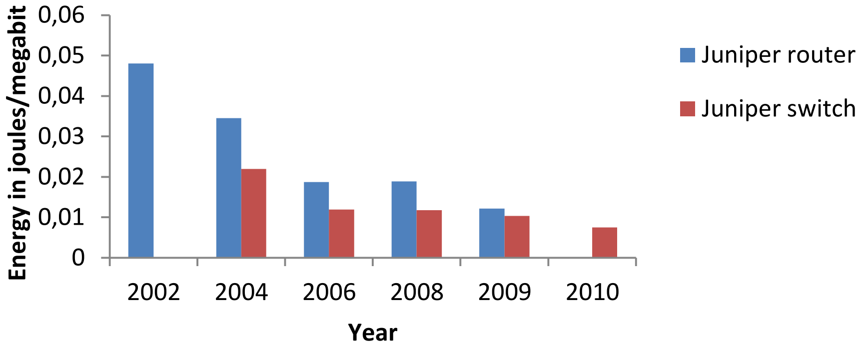

Figure 29: Energy per megabit comparison of Juniper router and switch

In ***Figure 29*** the comparison of power consumption of Juniper routers and switches are done for different years. It shows that Juniper routers consume more power than the switches. Enough data regarding the release dates of Juniper routers and switches during the same period is difficult to found.

5. Discussions and Conclusions

In this thesis, we presented a detailed energy consumption study of routers and switches across different type of manufacturers and devices based on publicly available datasheets. In some cases the manufacturers were contacted privately in a view to get the information which is not available to general public. Some of the analysis and the results presented might have been known by equipment vendors but have not been previously reported in the literature.

Study of energy efficiency of the routers and switches is a really interesting topic that involves a lot of data collection and analysis. From the collected data, energy consumption in joules per megabits of different vendors of routers and switches are analyzed and interpreted. Comparison of routers and switches of same vendors in different years is done for Cisco, Juniper, D-link, HP and Brocade networks. The most important result of this study is the amount of difference in power consumption found between the switches and routers of the same manufacturers during the same period of time. For most of the vendors the routers consume about 15-30 percentage more power than that of switches of same vendor in different years. So, we can say that the energy consumed by the router is far more than that by the switch for the various vendors. There is also difference in the power consumption of the routers and switches for different years regardless of the brand. However, this is due to the additional features and facilities that make the routers consume more power. Also, we can say that the switches are far better than the routers, when it comes to energy consumption. It has now been a global concern to design energy efficient routers and switches at an affordable reliable price that can provide maximum possible capacity. An approach for transmission without using the routers can be viewed as an option for the future as switches are far better in case of energy consumption than the routers. Other results were expected, but are worth mentioning, given its importance in the field of green networking. For instance modularity including the additional features and services of the devices comes at a very much higher power expense than fixed service devices. So, this might lead to re-thinking for network planners to carefully decide if particular features or functionalities are really essential or not and if they are worth the significant energy consumption cost.

Not much information could be collected about the information regarding the release dates of the routers and switches as only few manufacturers made it available in their datasheets. We think that this is the most important parameter required for study on power consumption of devices over the years. It is also crucial to study the improved performance of devices in certain periods of time so it is necessary that the manufacturers provide it in a systematic way. As we know that a thorough study of the devices are necessary for designing and operating energy efficient networks ,we believe this thesis can be helpful for further comparisons and analysis.

6. Future Works

We know that a significant portion of power is consumed by the basic systems such as cooling system, supervisor system, routing and forwarding systems. The assessment of ratio of energy consumption between the basic configuration of empty chassis and the full loaded chassis case is important for proper power management perspective of the devices. Physical specifications such as physical dimensions, weight, and type of physical connections also have a direct impact on the network power consumption. While fixed configuration devices occupy smaller space, chassis-based devices need a larger space. So, it is worth mentioning the effect of devices volume in case of power consumption. Apart from this, study of whether the equipment power consumption differs according to the part of the network where it is deployed is also an interesting topic for the further research.

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Appendix A

Data of different manufacturer of routers

Manufacturer	Released year	Power (Watt)		Performance (Gbps)			
		typical	max	typical	max	energy /MB(max)	energy/MB (typical)
CISCO NETWORKS							
CISCO							
1800	2002	80	90		1,6	0,05625	
1900	2003	85	110	0,025	3,2	0,034375	3,4
2800	2004						
2801		42	120	0,1	1,6	0,075	0,42
2811		32	160	0,1	3,2	0,05	0,32
2821		54	240	0,75	5,2	0,046153846	0,072
2851		58	360	0,1	5,2	0,069230769	0,58
2900	2006			0,075			
2901		40	150	0,075	6,4	0,0234375	0,533333333
2911		50	210	0,075	10,4	0,020192308	0,666666667
2921		60	320	0,075	10,4	0,030769231	0,8
2951		70	340	0,075	14,4	0,023611111	0,933333333
3900	2008			0,35			
3945E		158	540	1	20,8	0,025961538	0,158
3925E	2008	150	420		12,8	0,0328125	
3945		105	540		22,4	0,024107143	
3925	2008	100	420		14,4	0,029166667	
7200	2009	85	150	1,5	8,4	0,017857143	0,056666667
7500	2010		100	2	5	0,02	
JUNIPER NETWORKS							
JUNIPER							
E320	2002		3347		320	0,010459375	
E120			1638		120	0,01365	
J4350	2006		143	1	11	0,013	
J6350	2006		166	2	12	0,013833333	

J2350	2006		80	0,75	9,75	0,008205128	
J2320	2006		75	0,6	7,6	0,009868421	
MX80	2009		500		80	0,00625	
MX240	2009	1400W	1485		240	0,0061875	
MX480	2009	1360+ 310	1830		480	0,0038125	
MX960	2009	6160 W	6160		960	0,006416667	
M20	1999		706		20	0,0353	
M5	2000		434		5	0,0868	
M10	2003		434		10	0,0434	
M160	2000		1785		12,8	0,139453125	
M7I	2004		378		20	0,0189	
M320	2004		3175		320	0,009921875	
M40E	1998		2600		260	0,01	
G10	2001		1800				
SSG140	2007				3,5	0	
DLINK NETWORK							
DLINK							
DAP1522	2005						
DAP-1160	2010		40		4	0,01	
DAP-1350	2009		7		0,3	0,023333333	
DAP-1353	2008		9		0,3	0,03	
DAP-1360	2009		5		0,3	0,016666667	
DAP-1555	2007		8		0,3	0,026666667	
DFL-210	2004						
DES-1024D	1999						
DES-1008D	2003						
DFL-160	2010		20		1	0,02	
DFL-1660	2009		6,6		0,225	0,029333333	
DI-624	2003		7		0,054	0,12962963	
DI-524	2004		6		0,054	0,111111111	

DIR-655	2006		14		0,3	0,046666667	
BEFSR41	2004		15		0,1	0,15	
BEFVP41	2002		25		0,1	0,25	
G300NH	2010		14		0,3	0,046666667	
BROCADE NETWORKS							
BROCADE							
MLXe-4	2008		1730		436,363	0,003964589	
MLX-4	2008		1389		349,09	0,003978917	
MLXe-8	2009		3356		872,7272	0,003845417	
MLX-8	2009		2760		698,18	0,003953135	
MLXe-16	2009		5698		1745,455	0,003264478	
MLX-16	2009		5591		1381,181	0,004047985	
MLXe-32	2010		11414		3490,9	0,003269644	
MLX-32	2010		11391		2763,63	0,004121753	
CER 2024C			135		48	0,0028125	
CER series							
2024F			160		48	0,003333333	
2048C			240		96	0,0025	
2048F			280		96	0,002916667	
HP NETWORKS							
HP							
JF233A	2006		100		1	0,1	
JF284A			125		20	0,00625	
JF803A	2010		210		54	0,003888889	
JF816A			54		2	0,027	
JF802A			125		30	0,004166667	
(J8752A)	2005		15		1	0,015	
J8753A	2005		50		5,4	0,009259259	
G300NH	2010		14		0,3	0,046666667	
JE468A					0,3	0	
EG200							
E4G2OO			49		12,94	0,003786708	

Appendix B

Data related to different manufacturer of switches

Manufacturer	Released date	Series	Capacity (Gbps)	Power (watt)	energy /MB
CISCO NETWORKS					
CISCO	2004	520-8P	3,6	60	0,016666667
		520-24	12,8	180	0,0140625
		520-24P	12,8	180	0,0140625
		520-48	17,6	370	0,021022727
		520-48P	17,6		0
	2006	540-8P	18	123	0,006833333
		540-24	48	280	0,005833333
		540-24P	48	280	0,005833333
		540-48	96		0
	2008	2955T-12	6,4	23	0,00359375
		2960G-8TC	8,6	22	0,00255814
		SG200-08	8,6	35	0,004069767
	2010	2960-S Series			
		2960S-24TS-S	50	36	0,00072
		2960S-24TS-L	176	50	0,000284091
		2960S-48TS-S	50	53	0,00106
		2960S-48TS-L	176	55	0,0003125
	2011	3750-24FS	100	56	0,00056
	2003	2970G-24TS	19,8	190	0,00959596
		2970G-24T	18,28	160	0,008752735
	2002	SFE2000P	17,6	360	0,020454545
	2007	2950-24	3,6	30	0,008333333
	2011	2950T-48	10,1	45	0,004455446
	2011	2955T-12	6,4	23	0,00359375
HP NETWORKS					
HP	2006	2910al-24G	1	20	0,02
		3Gb SAS BL	3	40	0,013333333
		4208vl	10	630	0,063
	2007	1700 series	8,4	24	0,002857143
	2008	E2610-24	12,8	62	0,00484375
		E2910-24G al	128	82	0,000640625
	2006	J9079A	3,4	18	0,005294118
	2006	J9080A	8,4	24	0,007142857
	2006	J9079A	3,4	18	

	2006	J9080A	8,4	24	0,002857143
JUNIPER NETWORKS					
JUNIPER		EX2200 series			
	2008	24P/24T	56	400	0,003636364
	2008	48P/48T	104	930	0,006818182
	2009	EX 3200 Series			0,002352941
		EX 3200-24T	88	320	0,006838235
		EX 3200-24P	88	600	
		EX 3200-48T	136	320	0,0019375
		EX 3200-48P	136	930	
					0,003636364
	2009	EX2500	480	930	0,006818182
	2010	EX4200 Series			0,003636364
		EX4200-24T	88	320	0,006838235
		EX4200-24P	88	600	
		EX4200-48T	88	320	
		EX4200-48P	136	930	
					0,03515625
DLINK NETWORKS					
DLINK					
	2004	DSS-24	4,8	39	0,006
		DES-1026G	8,8		0,000669444
	2008	DGS-3100	68	556	0,001215741
	2004	DWS-3227	10	60	0,000872917
	2009	DGS-3627	108	72,3	0,00065
	2009	DGS-3650	108	131,3	0,002613636
	2009	DGS-3200	48	41,9	0,002941176
	2006	DGS-1224T	48	31,2	
	2006	DES-3526	8,8	23	
	2006	DES-3550	13,6	40	0,001231061
BROCADE NETWORKS					
BROCADE	2010	ICX 6610-24	528	650	0,001231061
	2010	ICX 6610-48	576	680	0,001180556
		6430-24			
	2008	BROCADE 300	8	57	0,007125
		FCX SERIES			
	2009	FCX 624	128	350	0,002734375
	2009	FCX 648	176	420	0,002386364